CODIGEM

CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO-MINERO-METALÚRGICA

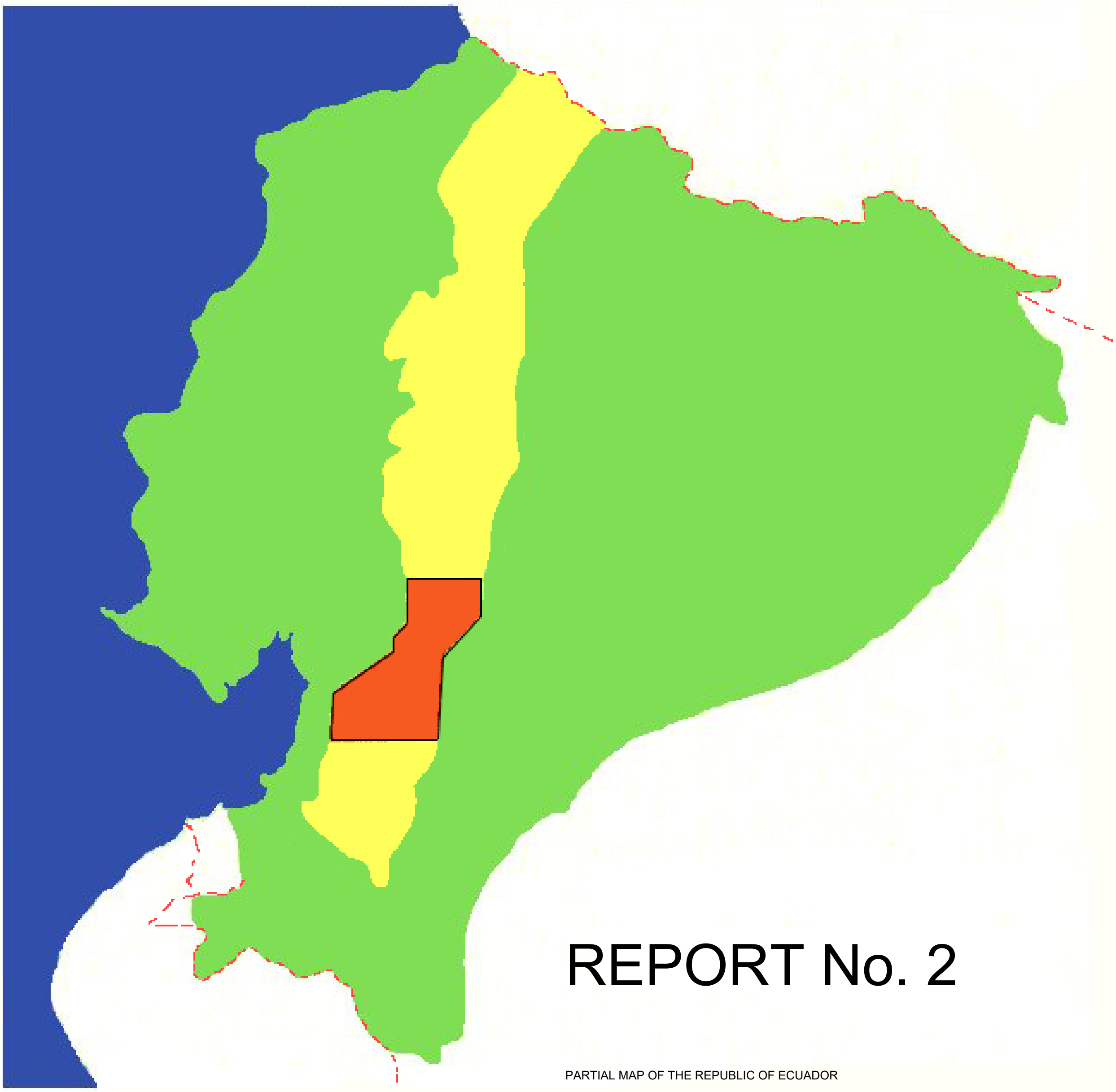
MINISTERIO DE ENERGÍA Y MINAS

DFID

DEPARTMENT FOR INTERNATIONAL DEVELOPMENT

BGS 1835

BRITISH GEOLOGICAL SURVEY



REPORT No. 2

PARTIAL MAP OF THE REPUBLIC OF ECUADOR

WORLD BANK MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME (WESTERN CORDILLERA)

PATRI MATRIQUE

MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME

Report Number 2

GEOLOGY OF THE WESTERN CORDILLERA OF ECUADOR BETWEEN 2°00' AND 3°00'S

Peter Dunkley

Alina Gaibor

CODIGEM-BRITISH GEOLOGICAL SURVEY

Quito-Ecuador

1997

Stalyn Paucar

2024 edition

Reference

Dunkley, P., & Gaibor, A. (1997). *Geology of the Western Cordillera of Ecuador between 2°00' and 3°00'S* (Stalyn Paucar, Ed., 2024). Report Number 2. Geological Information Mapping Programme. BGS-CODIGEM/MEM.

CONTENTS

FIGURES

TABLES

PLATES

APPENDICES

1. INTRODUCTION

This report describes the geology of the Western Cordillera of Ecuador between 2° and 3°S.

The report is based on a reconnaissance survey undertaken as part of the Geological Information and Mapping Programme (GIMP), which forms part of a larger multilateral technical assistance project, the *Proyecto de Desarrollo Minero y Control Ambiental* (PRODEMINCA), funded by the World Bank and the Governments of Ecuador, Sweden and the United Kingdom (Department for International Development).

One of the primary objectives of the Geological Information Mapping Programme is to promote development in the Mining Sector of Ecuador by providing an internally consistent geological database for the Western Cordillera. This programme is being undertaken by the British Geological Survey (BGS) and the Corporación de Desarrollo e Investigación Geológico Minero-Metalúrgica (CODIGEM).

Geological mapping of the Western Cordillera to the south of the equator began in 1995 with separate teams of geologists being deployed on each of the four-degree sectors between 0°-4°S. This first phase of mapping was completed in mid-1997, following which geological maps were published for the three southern degree sectors (BGS-CODIGEM, 1998a, 1998b, 1998c). Currently the survey is continuing north of the equator, and eventually two additional geological maps will be published for the two-degree sectors of the cordillera between 1°S and the border with Colombia.

Although this report is dated 1997, it was revised in 1998 following publication of the accompanying geological map sheet (BGS-CODIGEM, 1998b).

A regional drainage geochemical survey of the Western Cordillera is also being carried out as part of the Geological Information and Mapping Programme. The results of the geochemical survey for the 2°-3°S sector of the cordillera covered by this report are given in Williams et al. (1998).

Figure 1. Location of the mapped area

2. GEOLOGICAL SETTING OF THE PROJECT AREA

2.1 Modern tectonic setting of the Ecuadorian region

The Andes dominate the geology and structure of the region, and form a continuous mountain range more than 7000 km in length which extends along the entire pacific margin of South America. A deep-sea trench system lies to the west of the margin, along which oceanic crust of the Pacific is being subducted beneath the continent.

The Andean range may be divided into three segments, namely the Southern, Central and Northern Andes, each of which has different structural trends and magmatic histories and styles of metallogenesis (Gansser, 1973; Sillitoe, 1974). Ecuador straddles the central part of the Northern Andes. In broad terms the Nazca Plate is being subducted beneath the Ecuadorian sector of the continental margin. In detail young oceanic crust (<20 Ma) generated by the Nazca-Cocos spreading centre at the Galápagos Rift Zone is being obliquely subducted along the Ecuadorian trench with an angle of descent of 25-35°, and a convergence rate of approximately 9 cm per year (Lonsdale, 1978).

2.2 Regional structure of Ecuador

Ecuador is divided into three main physiographic areas. These are the “Sierra”, a sector of the Andean mountain chain that runs north-south along the central region of the country, and separates the Amazon basin or “Oriente” in the east from the coastal plain or “Costa” to the west.

The Oriente is a large sedimentary basin, including a platform carbonate sequence, which is underlain by older cratonic basement. Both the basin and the basement have been intruded by large granitoid batholiths, mainly located along the complex sub-Andean zone of folding and thrusting that separates the Oriente from the Sierra to the west.

The Costa comprises the whole region west of the Sierra and consists of a large alluvial plain underlain by Late Cretaceous to Cenozoic forearc sediments and accreted oceanic and island arc terranes, locally exposed in the hills of the Coastal Range.

The Sierra consists of two parallel mountain chains separated along much of their length by an axial graben, the Interandean Valley. The Cordillera Real to the east is dominated by linear belts of metamorphic rocks, intruded by early Mesozoic granitoids of both S- and I-type, capped along much of its length by Cenozoic calc-alkaline volcanic rocks. The Western Cordillera (Western Cordillera) to the west of the graben is dominated by Late Mesozoic to Early Cenozoic basaltic volcanic and volcanoclastic rocks and turbidite sequences, which are at least in part accreted oceanic terranes. These are overlain by post-Middle Eocene intermediate to acid calc-alkaline continental margin volcanic rocks, which together with the basaltic terranes to the west are intruded by middle to late Tertiary granitoids.

The axial intermountain graben, or Interandean Valley, is an extensional structure bounded for much of its length by active faults. It is infilled with sedimentary and volcanic sequences which probably date back to Oligo-Miocene times and is the locus of Quaternary volcanism which is manifested by a chain of modern stratovolcanoes.

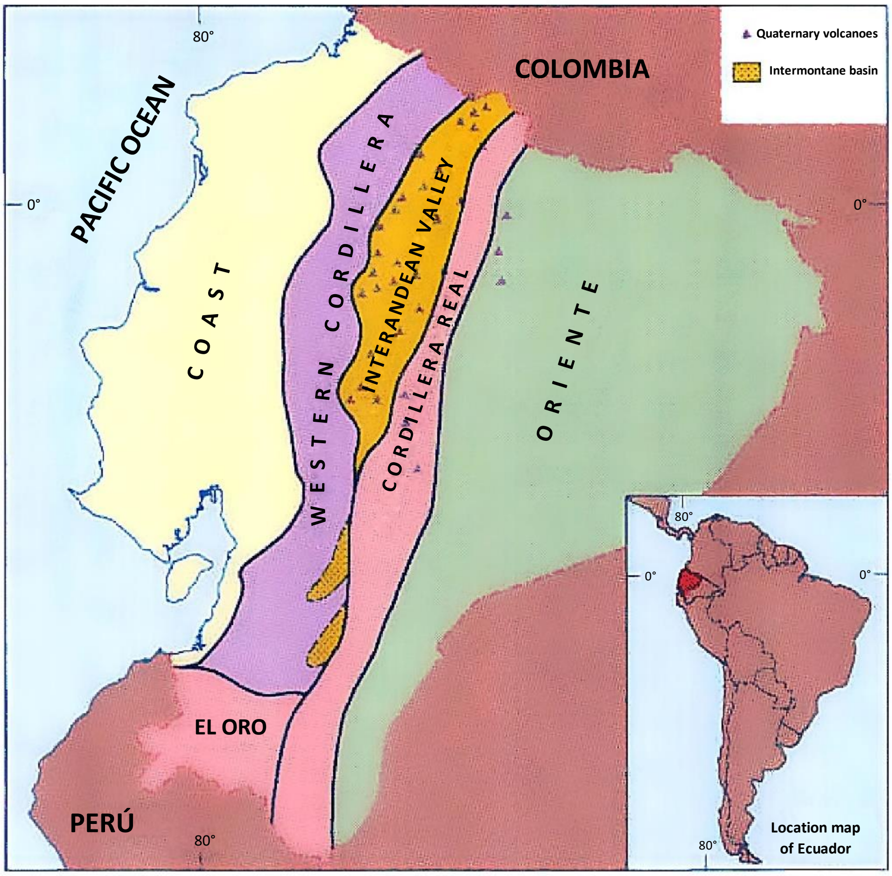


Figure 2. Simplified map showing the main tectonic elements of Ecuador

2.3 Summary of previous geological work in Ecuador

Wolf (1892) published the first map and comprehensive geological description of Ecuador. This remained the standard reference work until that of Sauer (1957, 1965), which included and complemented the earlier work of Tschopp (1948, 1953), based mainly on confidential studies of the sedimentary basins of Ecuador for the oil industry. Further systematic studies of the sedimentary basins were undertaken by the French Petroleum Institute, leading to the first geodynamic synthesis by Faucher and Savoyat (1973).

A systematic geological mapping programme was carried out by the Institute of Geological Sciences (IGS) (now the British Geological Survey) and the Dirección General de Geología y Minas (DGGM) during the period 1969-1980. This resulted in the publication of various 1:100000-scale geological maps and a new 1:1000000-scale national geological map and explanatory bulletin (MRNE-IGS, 1982; Baldock, 1982). Related publications from this period on the geology of Ecuador include those of Henderson (1979), Bristow and Hoffstetter (1977), Kennerley (1980) and Bristow (1981).

A second BGS-DGGM/INEMIN/CODIGEM technical co-operation project undertook a regional geological mapping and mineral potential survey of the metamorphic belts of the Cordillera Real and El Oro during the period 1986-1993 (Litherland et al., 1994; Aspden et al., 1995). This phase of work also saw the publication of a new national geological map and a tectono-metallogenic map at a scale of 1:1000000 (BGS-CODIGEM, 1993a, 1993b).

2.4 Summary of previous geological work in the Western Cordillera

Prior to the present project most interest had been concentrated on the geology of the central and northern sectors of the Western Cordillera, and little systematic work had been undertaken in the area covered by the present report. The following account of previous geological work within the cordillera is therefore cursory and only covers the development of ideas related to those rock units which are found within the mapped area.

The earliest studies by Wolf (1892) described the main rock types of the Western Cordillera and Coastal Range as "rocas porfídicas y rocas verdes". Tschopp (1948) subsequently introduced formal stratigraphical names for these sequences, introducing the name Piñón Formation for the basic volcanic rocks of the Coastal Range, while retaining Wolf's descriptive terms for the basic volcanic rocks of the Sierra. Sauer (1965) later used the term "Formación Diabásica-Porfirítica" for the basic volcanic rocks of the Sierra and also used the term "Yunguilla Formation", which had originally been introduced by Thalmann (1946) for marine turbidites of Maastrichtian age from the Quito-Nono region of the Western Cordillera.

Systematic mapping by geologists from the Institut Français du Pétrole in the mid-sixties led to the first correlation between the geology of the Coastal Range and that of the Western Cordillera. The name Piñón Formation was used for the Cretaceous oceanic basement, comprising "rocas verdes" and diabases. Goossens and Rose (1973) later proposed that these rocks be renamed the Basic Igneous Complex.

Subsequent ideas on the stratigraphy of the Western Cordillera were influenced by surveys undertaken by IGS/DGGM geologists, and in particular by the interpretation of Henderson (1979) who proposed that the basic volcanic rocks of the Cordillera and of the Costa were of different age and origin. The name Piñón was retained but restricted to ocean floor basaltic volcanic rocks of the Costa, while the name Macuchi Formation was created for the "rocas verdes" of the Western Cordillera which were interpreted as island arc volcaniclastic rocks based on a combination of lithological and geochemical evidence. Conglomeratic rocks, formerly known as the Cayo Rumi Formation in the Santo Domingo-Alóag road section were renamed the Silante Formation. These were interpreted to directly overlie the Macuchi volcaniclastic rocks, and were in turn thought to be overlain by the Yunguilla Formation of proven Maastrichtian to Palaeocene age. Farther south, to the east of Quevedo-La Maná, early Eocene fossils were reported from the Macuchi Formation, and andesite sills within the sequence yielded Middle Eocene K/Ar ages. In addition, Eocene fossils were recorded from the overlying "Yunguilla-type" flysch sequence. The Macuchi Formation and by inference the overlying flysch unit were therefore interpreted by Henderson to be strongly diachronous and were assigned a Cretaceous to Eocene age along the length of the cordillera.

The later work of Egüez (1986) in the central sector of the Western Cordillera partly resolved the Macuchi-Yunguilla dilemma introduced by Henderson (1979, 1981). Egüez demonstrated the presence of two lithologically similar turbidite sequences of differing ages which had previously been mapped as a single unit, the Yunguilla Formation. The true Yunguilla Formation was known to be of late Cretaceous to Early Palaeocene age, and the younger sequence, the Apagua Formation, was shown to be of middle Eocene or younger age. Egüez restricted the term Macuchi (*sensu stricto*) to a volcanic-volcanosedimentary unit of Early to Middle Eocene age, and also recognised the presence of true ocean floor basalts, which he named the Toachi Unit and equated with the Piñón Formation of the Costa.

The geochemical studies of Lebrat (1985) showed that the Macuchi Formation of Henderson included tholeiitic island arc basalts, oceanic MORB and calc-alkaline basalts. The MORB rocks were correlated with the Piñón Formation of the Costa and the calc-alkaline volcanic rocks were mistakenly correlated with the Cretaceous Celica Formation of southern Ecuador (whereas the present study indicates they belong to the Eocene-Miocene Saraguro Group). Similarly, Van Thournout et al. (1992) recognised three volcanic sequences in the north-western part of the Western Cordillera. These included Early Cretaceous MORB basalts, an Eocene sequence of island arc tholeiitic to calc-alkaline basalts and an Oligocene sequence of calc-alkaline volcanic rocks of mainly andesitic and dacitic compositions. In the latest version of the national geological map (BGS-CODIGEM, 1993a) the pre-Oligocene volcanic rocks of the Western Cordillera were divided into a Palaeocene to Eocene island arc sequence, the Macuchi Unit, and a pre-Senonian ophiolitic sequence named the “Piñón of the Sierra”.

A large part of the Western Cordillera in southern Ecuador (which includes the area of this report) is composed of Cenozoic calc-alkaline continental margin volcanic rocks of intermediate to acid composition. Earlier mapping of the region included large areas of these rocks in the Tarqui Formation (uppermost Miocene) or within the Macuchi Formation (*sic.*), as for example on the geological map of the Cuenca area (DGGM, 1980b). The latest edition of the national geological map (BGS-CODIGEM, 1993a) assigned these sequences to either the Volcánicos Pisayambo of assumed Late Miocene-Pliocene age, or to the Volcánicos Saraguro of assumed Oligocene age.

One of the most important aspects of the current work has been a relatively detailed study of the Cenozoic volcanic rocks of the area, most of which have been redefined as the Saraguro Group. The name Saraguro had previously been associated with some of these rocks (Baldock, 1982; BGS-CODIGEM, 1993a), but is now used in a more restricted sense for undivided volcanic sequences of Oligocene age. The present work has shown the Saraguro Group to be made up of a considerable number of different volcanic units of late Middle Eocene to Early Miocene age. Within the area covered by this report, the group includes almost all of the rocks previously thought to be much younger and mapped as the Pisayambo Volcanics and Tarqui Formation, as well as rocks which were formerly considered to be older and were mapped as the Macuchi Formation.

3. DESCRIPTION OF THE AREA AND WORKING METHODS

3.1 Physiography of the area

The mapped area covers about 6300 km^2 of the Western Cordillera between 2° and 3° S.

The area is bounded on the west by the Costa, a broad coastal plain between 15 and 100 km wide, which extends westwards from the foothills of the Cordillera to the Pacific Ocean. Numerous large alluvial and colluvial fans are developed along the base of the western foothills where rivers disgorge from the cordillera onto the coastal plain.

In the south-east of the mapped area the Western Cordillera is bounded on the east side by the Cuenca basin. This is a large intermountain sedimentary basin, of Miocene to Recent age, situated between the Western Cordillera and the Cordillera Real, at an altitude of between 2500 and 2800 m. The Cuenca basin dies out to the north of the Río Cañar and the Western Cordillera is juxtaposed against the Cordillera Real with no intervening intermountain depression.

The Río Cañar flows through the Western Cordillera from east to west at the latitude of about 2°30’, and divides the mapped area into two distinct regions. The largest physiographic block lies to the south of the Río Cañar and consists of a high mountainous area that is largely uninhabited. The eastern part of this block, in the Cajas-Gualleturo-Chiquintad area, is occupied by a rugged, glaciated area of páramo with numerous lakes and areas of peat bog. The altitude is generally between 3500 and 4000 m, although numerous rocky peaks rise above this level, reaching a maximum of about 4500 m in the Filo Cajas [6932-96967]. Rivers rising on this high ground flow radially away to the Costa in the west, to the Río Cañar in the north and to the Cuenca basin in the east. In the high páramo they flow through broad glaciated valleys characterised by rock steps, and rock basins containing lakes. Passing off the high páramo the western flanks of the cordillera descend rapidly to the coastal plain and the rivers here are fast-flowing torrents in deeply incised valleys and ravines. In contrast, the northern and north-western flanks of the Cajas block have the form of broad, moderately inclined dip-slopes capped by lavas, but below about 3000 m they plunge precipitously down to the Cañar Valley. Similarly, the eastern flanks of the Cajas area have the form of a broad slope capped by lavas, which dips with moderate gradients down to the Cuenca basin.

To the north of the Río Cañar the terrain is broken into several smaller physiographic blocks by the fault-controlled valleys of the Ríos Chimbo and Chanchán. Drainage patterns are complex, but all the rivers flow westwards and south-westwards. Most join either the Chimbo, Chanchán or Cañar rivers and thence flow westwards to the Costa. This northern part of the area increases in altitude towards the east and culminates in a plateau along the eastern margin of the cordillera between Zhud and Tixán. These plateaus generally exceed 4000 m in altitude and locally reach heights of about 4400 m in a series of table-top mountains, the highest of which is Cerro Cisarán. Along much of the eastern margin of the area north of the Río Cañar there is no Interandean valley and therefore no clear topographic distinction exists between the Western Cordillera and Cordillera Real.

In the north-east of the area, around Palmira, the Interandean Valley is again developed. It consists of an undulating plain at an altitude of around 3000 m, which is bounded to the west by the higher ground of the Western Cordillera, composed largely of volcanic rocks, and to the east by the metamorphic terrain of the Cordillera Real. The plain is underlain by young fluviolacustrine sediments and volcanic ash, which because of their porous nature give rise to a semi-arid environment characterised by superficial deposits of windblown sand and ash with patches of residual gravel.

3.2 Access

Access within the area is generally poor, particularly in the high ground south of the Río Cañar.

Main roads run north-south along the eastern and western margins of the area. These include the Panamerican highway which runs along the floor of the Cuenca basin between Cuenca and Cañar, and then passes northwards along the eastern margin of the area via Zhud and Alausí to Palmira, and thence farther north towards Riobamba. A main road also runs parallel to the cordillera along the coastal plain a short distance to the west of the foothills. This passes northwards from Machala via Naranjal, La Troncal, El Triunfo and Cumandá and then cuts north-eastwards along the Chimbo valley to Pallatanga and thence to Riobamba.

Several important roads cut across the cordillera, linking the coastal route in the west with the Panamerican highway to the east. These include the spectacular new road between Cuenca and Jesús María, via San Felipe de Molleturo, and the Zhud to La Troncal road, which passes through Suscal. Lesser used dirt roads cross the north of the area between Alausí and El Triunfo via Huigra, and between Alausí and Pallatanga.

Road access through the main part of the area south of the Río Cañar is very poor. Apart from the main Cuenca-Jesús María route, the only other motorable roads are from the Costa to Carmen de Pijilí in the south-west of the area, from Cuenca westwards to Chaucha and Pimo, and between San Antonio de Gualleturo and Cañar along the south side of the Cañar valley. Apart from a few small and isolated communities, much of the high ground to the south of the Río Cañar is uninhabited. As a result, there are few footpaths, and this combined with the altitude and rugged nature of the terrain makes access on foot difficult and slow.

The area north of the Río Cañar is generally more populated and has many small communities and villages. As a result, this ground is better served by secondary roads and has a network of footpaths which enable most parts of the area to be reached by vehicle and on foot without major difficulties.

3.3 Previous geological maps of the area

Previous geological maps of the area were published at scale of 1:100000. These include the sheets for Alausí (DGGM, 1975a), Cañar (DGGM,1975b), Bucay (DGGM,1979), Gualleturo (DGGM,1980a), Cuenca (DGGM,1980b) and Azogues (DGGM,1980c). These vary greatly in detail and quality. The areas of the Cuenca basin were mapped in considerable detail, and the stratigraphy and maps have largely stood the test of time. In contrast, the geology of the cordillera between 2°-3°S was mapped by these earlier surveys in a very cursory manner. As a result, the previously published geological maps of the area bear little resemblance to the map produced during the present project.

3.4 Working methods

Fieldwork was carried out between September 1995 and January 1996, and between May and November 1996. Each field excursion lasted approximately three working weeks, amounting to about 170 days in total, including time for mobilisation.

Geological traverses were initially undertaken along the roads of the area and subsequently numerous selected traverses were carried out on foot. The high ground south of the Río Cañar was examined by a number of traverses radiating away from the small settlement of Patul in the centre of the area. These longer traverses used mules for transporting equipment and provisions and each lasted approximately a week.

Details of localities were recorded in the field on locality forms which were numbered sequentially and prefixed by the initials PND. In addition to descriptions of the geology, each locality form included information such as UTM coordinates, the name and code of the 1:50000 topographical map and sample numbers. Locality and sample numbers and geological information were entered on 1:50000 topographical maps in the field. Locality and sample numbers were transferred to plastic overlays of each 1:50000-scale topographic map in the office. In total 2082 localities were examined and more than 1000 samples were collected. From these samples, 282 were selected for the preparation of thin sections and petrographic examination. Locality forms, field maps, sample and locality maps, samples and thin sections are archived in the offices of CODIGEM in Quito.

Chemical analyses of 62 rock samples were obtained. These included 22 tuff samples from the Saraguro Group which were analysed for major elements at the laboratories of Bondar Clegg in Vancouver, and 40 lava samples that were analysed for major and trace elements at the British Geological Survey and University of Leicester. The chemical analyses were used to classify the volcanic rocks using the IUGS-recommended TAS system (Le Maitre, 1989).

Gamma-ray spectrometer readings were taken at most outcrops examined during the second year of the project using a portable EDA instrument. These proved to be a valuable aid to evaluating rock compositions. The instrument measured gamma-ray counts for five channels, including two channels for total gamma radiation of different energy levels, and three channels specifically for uranium, thorium and potassium. A suite of tuffs from the Saraguro Group were analysed chemically and good linear correlations were found to exist between the intensity of gamma radiation and SiO_2 and K_2O contents. It was therefore possible to use gamma-ray measurements in the field to obtain fairly reliable estimates of tuff compositions. The general relationship of increasing gamma radiation with increasing SiO_2 and K_2O also held for the lavas of the area but was less clear. Details of the relationship between gamma radiation and chemical composition are given in Appendix 1.

Fourteen new radiometric dates were obtained during the course of the survey. Twelve samples were dated by the fission-track method on zircons at the Geological Institute of the Swiss Federal Institute of Technology in Zürich by Steinman (1997a), and two samples were dated by the K/Ar method on amphibole separates at the Scottish Universities Reactor Centre in East Kilbride.

Complete aerial photographic coverage of the area was obtained from the Instituto Geográfico Militar (IGM). Photographs varied in scale from approximately 1:40000 up to 1:60000. The general quality of the photographs was poor and little useful information could be obtained except for that on fracture patterns.

Landsat TM images were digitally processed at BGS Nottingham and false colour photographic copies were provided to the project in Ecuador for interpretation at scales of 1:100000 and 1:250000. The images used were Landsat scenes 010-61 and 010-62 both of which were acquired on 16 March 1987. The images were produced by combining bands 4, 5 and 7, and applying a contrast stretch and edge enhancement correction. They provided a good overview of the area, but were generally of little use for the recognition of lithologies and structures, except for fracture patterns. One of the main problems is that the images suffer from cloud cover over the western flanks and foothills of the cordillera.

Satellite radar images were also obtained for the area at scales of 1:100000 and 1:250000. The imagery was acquired by Radarsat on 25 October 1996 and was processed at BGS in Nottingham using a combination of smoothing, edge enhancement and contrast stretching. The images were found to be useful in recognising lineaments or fracture traces, particularly along the western flanks of the cordillera where the Landsat TM images suffered from thick cloud cover. Both the Landsat and Radarsat images for the area may be obtained from BGS Nottingham on request.

Geological maps were compiled at a scale of 1:100000, of which there are 6 complete or partial maps covering the area. These were digitised and the data was reduced to a single map of 1:200000-scale for publication (BGS-CODIGEM, 1998a). The digitised data from the 1:100000-scale maps is held within the project's computer database/GIS at the CODIGEM offices in Quito.

4. LITHOSTRATIGRAPHY

4.1 Introduction to the stratigraphy of the area

Several major NE-trending fault systems divide the area into a number of zones of contrasting geology.

By far the largest zone is situated to the southeast of the Bulubulu Fault and is composed of a basement of metamorphic rocks overlain by Cenozoic continental margin calc-alkaline volcanic rocks of intermediate to acid composition. These include the newly defined Saraguro Group of Middle Eocene to Early Miocene age, and the Cisarán and Quimsacocha formations of Late Miocene age. Sediments of the intermountain Cuenca Basin occur along the eastern margin of the area in the southeast. These are largely fluvial in origin, but also contain lacustrine beds and fossil evidence for marine incursions (Steinmann, 1997b). Units of the basin which impinge on the margins of the area include the Middle Miocene Ayancay Group and the Late Miocene Turi Formation.

Allochthonous oceanic basalts of the Pallatanga Unit occur in a belt immediately northwest of the Bulubulu Fault. These are of probable Cretaceous age and are overlain by, and tectonically interleaved with Maastrichtian turbidites of the Yunguilla Unit. The Pallatanga and Yunguilla units are bounded to the northwest by the Multitud Fault, which separates them from a deformed belt of (younger) Palaeocene to Eocene turbidites of the Angamarca Group. This younger belt of turbidites is in turn bounded along its northwestern margin by the Chimbo-Cañi Fault, to the northwest of which lies another allochthonous terrane consisting of basaltic and andesitic volcaniclastic rocks and lavas of the Macuchi Unit, which represent an accreted island arc of Early Eocene and possibly Palaeocene age.

A simplified geological map showing the main lithostratigraphical units of the area is given in Figure 3, and the relationships between these are illustrated in the generalised vertical sections of Figure 4. The lithology, stratigraphical relationships and palaeoenvironments of the various rock units are described in the following pages in approximate ascending order of age.

4.2 Metamorphic rocks (M)

Metamorphic rocks were previously only known from a few isolated localities within the area, but mapping by the present project has shown them to be considerably more extensive than hitherto realised. They crop out in three main areas. In the north-east around Guasuntos [7445-97535] they are contiguous with metamorphic rocks of the Cordillera Real to the east. Farther south they form an extensive linear belt in the western central foothills of the area. In the south-west a zone of metamorphic inliers extends southwards from Molleturo through Chaucha into the adjoining map area to the south.

4.2.1 Metamorphic rocks in the Guasuntos area

Dark-grey to almost black phyllites and phyllitic schists with thin beds of quartzite and veinlets of quartz crop out around Guasuntos. These are contiguous with the metamorphic rocks of the Cordillera Real to the east and are unconformably overlain and intruded by andesites of the Cisarán Formation. Litherland et al. (1994) referred to these rocks as the Guasuntos Unit, including them within the Guamote Terrane, the protolith of which was considered to be a marine sequence of Lower Jurassic or possibly Lower Cretaceous age.

4.2.2 Metamorphic rocks in the central-western part of the area

The most extensive metamorphic rocks of the area crop out in a NE-trending linear belt more than 40 km in length, which extends from the Quebrada Palamá [7150-97426] near Huigra in the north to the headwaters of the Río Putucay [6820-97100] in the south where it is cross-cut by the Molleturo diorite.

The belt is largely fault-bounded. To the north-west it is everywhere faulted against basalts of the Pallatanga Unit along the Bulubulu Fault System. To the south-east the metamorphic rocks are faulted against, and unconformably overlain by the volcanic rocks of the Saraguro Group. Throughout much of its length the axial part of the belt is occupied by a linear granodiorite intrusion which locally shows the effects of shearing.

To the north of the Río Cañar the rocks of this belt consist mainly of grey to almost black graphitic phyllites, phyllitic schists and quartzites with a near-vertical NNE-trending schistosity. At several localities the protolith of these rocks can be clearly recognised, as for example around La Delicia [6940-97257] and a short distance to the north on the old La Troncal-Javín road [6971-97266]. Here they consist of thin-bedded quartzitic sandstones, siltstones and mudstones of probable turbiditic origin. Mature quartz conglomerates also occur at [7059-97353] and [6943-97272], and at the latter locality they appear to be confined to a cross-cutting channel structure within the finer sediments.

At many localities the metasediments show the effects of strong shearing, including the development of S-C mylonitic fabrics and a strong horizontal lineation, thought to have been caused by movement along the Bulubulu Fault system.

The schists are contact metamorphosed at the margins of the granodiorite which intrudes the axis of the belt. For example, near the contacts at La Delicia large euhedral chiastolite crystals can be seen cross-cutting the main schistosity and a later crenulation cleavage. Trouw (1976) also reports the occurrence of sillimanite at this locality.

The petrography of the rocks of this belt has not been studied in detail, but they mainly appear to be of low metamorphic grade and probably partly owe their schistosity to the effects of dynamic metamorphism due to movements along the Bulubulu Fault.

However, metamorphic rocks of much higher grade also occur. For example, in the Quebrada Palamá at the northern end of the belt, Egüez et al. (1988) report the occurrence of boulders of biotite gneisses with blue quartz, which were subsequently interpreted as metagranites by Litherland et al. (1994). High-grade rocks also occur within the belt to the south of the Río Cañar. For example, the section along the Río Patul between [6886-97117] and [6886-97136] exposes relatively coarsely crystalline biotite-muscovite schists and quartzites with ptygmatic quartz veinlets, which in places are almost gneissic. Retrogressed fibrolitic sillimanite and andalusite have been identified within these schists (PND-1398) (P. Duque, personal communication, 1997).

4.2.3 Metamorphic rocks in the Molleturo-Chaucha area

Metamorphic rocks occur in the south-west of the area in a zone of faulted inliers and roof pendants within and at the margins of the Chaucha batholith. The inliers are controlled by NE-trending faults which in several areas juxtapose the metamorphic rocks against oceanic basalts of the Pallatanga Unit to the west. The zone extends south-westwards from Molleturo through Chaucha and into the area of the adjacent map sheet. It appears to be a continuation along the strike of the metamorphic belt described in the previous section, having been cross-cut and separated from it by the intrusion of the Molleturo diorite.

The most northerly inlier occurs at an altitude of 3600 m within volcanic rocks of the Río Blanco Formation, at the north-western end of the ridge of Cerro Llapín [6770-96904]. Here coarsely crystalline biotite schists and quartzites outcrop, which in places are gneissic.

Metamorphic rocks are well-exposed in the ridge of Llin Alto [6735-96805], situated a few kilometres to the north of San Gabriel de Chaucha. They consist of muscovite and chlorite schists, quartzites and deformed conglomerates. In places the rocks are strongly mylonitic and the conglomerates contain stretched pebbles. Similar rocks also occur to the south of San Antonio de Chaucha in the area between Loma de Gurgur [6780-96775] and Naranjos [6763-96763]. At the contact with the Chaucha batholith they are strongly mylonitic and silicified. Andalusite and sillimanite were reported from these rocks by an earlier Belgian project (Misión de Bélgica, 1986) and petrographic examination of a limited number of samples during the present project identified the presence of retrogressed sillimanite, andalusite and garnet.

The metamorphic rocks farther to the south of Chaucha were not examined in the field, although widespread samples of schists and phyllites were collected from the area by the project’s geochemical sampling teams. This belt of metamorphic rocks extends south-westwards into the ground of the adjacent map sheet where a range of rock types are reported to occur, including graphitic phyllites, muscovite schists, biotite schists and garnetiferous gneisses and granitoid rocks (Pratt et al., 1997; BGS-CODIGEM, 1998c).

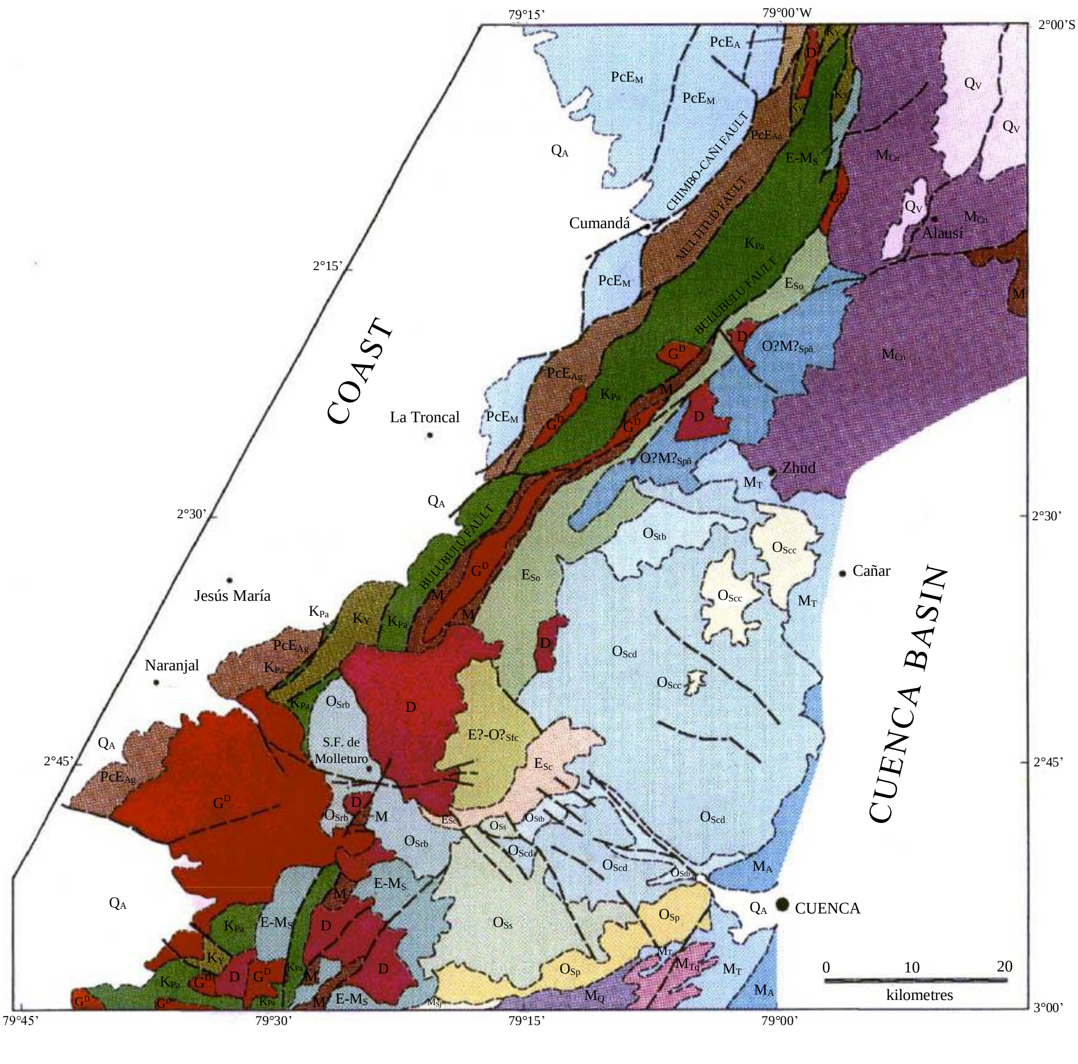


Figure 3. Simplified geological map of the area

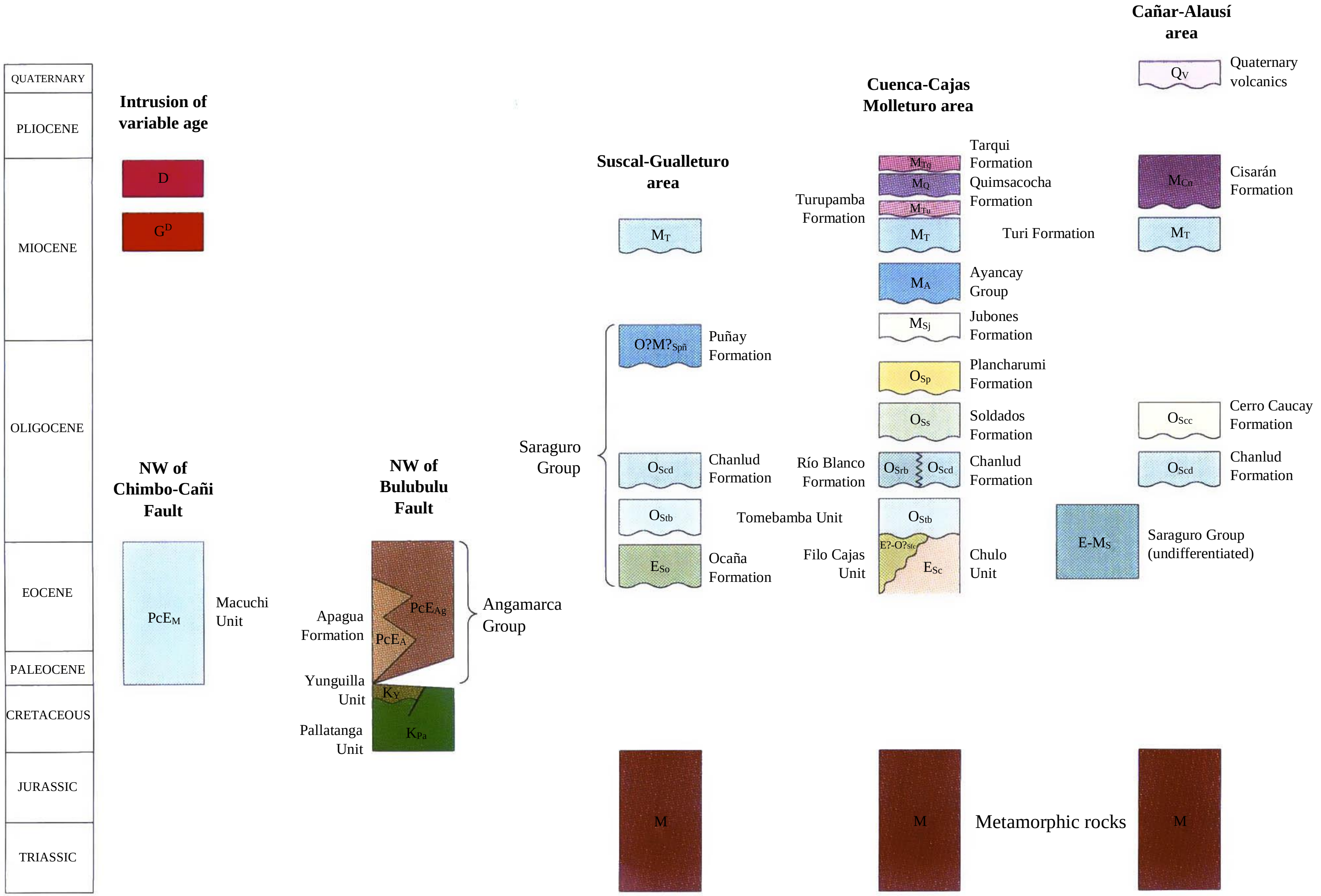


Figure 4. Stratigraphical legend (no vertical scale)

4.2.4 Summary and discussion of the metamorphic rocks of the area

The mapping of the present project has shown that the metamorphic rocks of the area are considerably more extensive than previously recognised. They crop out in a broken line of inliers which extends from Guasuntos in the north-east to the Chaucha area in the south-west, and from there southwards into the ground of the adjacent map sheet.

The present work also indicates that the Bulubulu Fault system is a fundamental tectonic structure, which separates metamorphic rocks to the south-east from allochthonous oceanic basalts of the Pallatanga Unit to the north-west. Based on the distribution of metamorphic inliers, it is concluded that to the south-east of the Bulubulu Fault System the volcanic cover rocks of the Western Cordillera are underlain by metamorphic basement, which is broadly contiguous with the metamorphic terrane of the Cordillera Real to the east.

The metamorphic rocks of the area are mainly low-grade metasediments, although high-grade rocks also occur. At some localities the higher-grade metamorphism is clearly a later contact phenomenon superimposed on the low-grade metasediments at the margins of granitoid intrusions. However, not all the high-grade rocks can be explained in this manner: the occurrence of blue quartz-bearing metagranites in the Huigra area and of garnetiferous orthogneisses in the area immediately to the south of the map indicate that the metamorphic basement is more complex. Such complexity accords with the hypothesis of Litherland et al. (1994) that much of the area is probably underlain by a metamorphic terrane, termed the Chaucha terrane, thought to be composed of Late Palaeozoic sediments affected by a Triassic orogeny.

4.3 Pallatanga Unit (K_{Pa})

The Pallatanga Unit was defined by McCourt et al. (1997) from the Pallatanga region, situated immediately to the north of the area. Here it consists of an assemblage of sheared and tectonically interleaved sediments, basalt lavas and gabbroic and ultrabasic intrusive rocks.

In the area covered by this report the Pallatanga Unit consists of a thick sequence of massive and pillowed basalt lavas with minor amounts of hyaloclastite and rare occurrences of gabbro. It crops out in an almost continuous NE-trending belt, extending from the northern margin of the mapped area near Pallatanga, south-westwards as far as the Cuenca-Jesús María road, to the south-west of which it is cross-cut by the Chaucha batholith. In the south-west of the area around Carmen de Pijilí, hornfelsed basalts occur at the margins of the batholith and are preserved as roof pendants. These can be traced farther south-west into the Ponce Enríquez area of the adjoining map sheet (BGS-CODIGEM, 1998c).

4.3.1 Contact relationships and age of the Pallatanga Unit

The Pallatanga Unit is everywhere fault-bounded, except where it is in contact with intrusions. On the south-east side the unit is bounded by the Bulubulu Fault which juxtaposes it against sheared metasediments and schists. Turbiditic sediments of the Yunguilla Unit of Maastrichtian age are tectonically interleaved with the basalts in some areas. Along the north-western margin the basalts of the Pallatanga Unit and the turbidites of the Yunguilla Unit are faulted against the Angamarca Group.

In the Cuenca-Jesús María road section, the basalts of the Pallatanga Unit are highly sheared and unconformably overlain by undeformed volcanic rocks of the Río Blanco Formation of the Saraguro Group.

The age of the basalt of the Pallatanga Unit is unknown, but a tentative correlation with the Piñón Formation of the Coastal Range implies a Middle Cretaceous, pre-Senonian age.

4.3.2 The Pallatanga Unit in the north of the area

Three accessible and well-exposed sections cut perpendicularly across the strike of the unit in the north of the area. These are the road sections along the Chanchán valley west of Huigra, between La Clementina [709-9750] and the Río Angas [715-9743], the road to Loma San Nicolás [726-9756], situated 7 km to the north of Huigra, and the Pallatanga-Alausí road between San Francisco de Multitud [724-9765] and Río La Esperanza [728-9761]. In these sections the unit consists of a thick sequence of pillowed, massive and brecciated basalt lavas with hyaloclastites. The basalts are fine grained, aphyric and at many localities strongly amygdaloidal with tubular amygdales infilled with calcite. The hyaloclastites occur in interstitial areas between pillows and as thin irregular intercalations, consisting of dark green, chloritised glassy shards and pillow selvages. Well-developed hyaloclastites are exposed near the end of the road at Loma San Nicolás.

A small body of sheared gabbro occurs within the basalts at [7277-97642] where the Alausí-San Francisco de Multitud road crosses the Quebrada Esperanza Vieja. Where the gabbro is undeformed it has a medium-grained ophitic texture.

4.3.3 The Pallatanga Unit in the central part of the area

The basalts can be traced in a continuous belt southwards from the Chanchán Valley along the prominent ridge leading to San Carlos Baja [6990-97309]. Farther south-west the Zhud-La Troncal road cuts perpendicularly across the belt and exposes a section through fine to very fine, massive and brecciated basalts with poorly preserved pillows. These are sheared and faulted against metamorphic schists at the eastern end of the section, and a medium-grained subophitic microgabbro occurs at the western end of the section [6925-97270].

The unit is also exposed in the lower reaches of the Patul River between [6829-97157] and [6854-97159]. Here it consists of very fine, dark-green basalts. Many of the outcrops along the river are almost black and flinty and extremely hard due to hornfelsing.

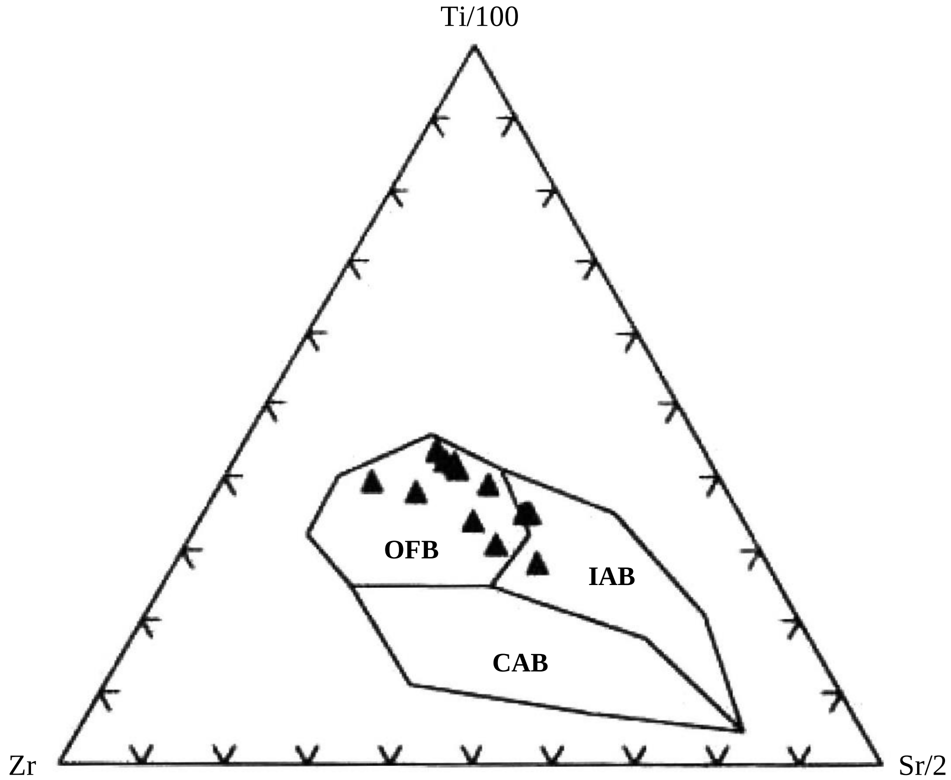


Figure 5. Ti-Zr-Sr discriminant diagram after Pearce and Cann (1973)

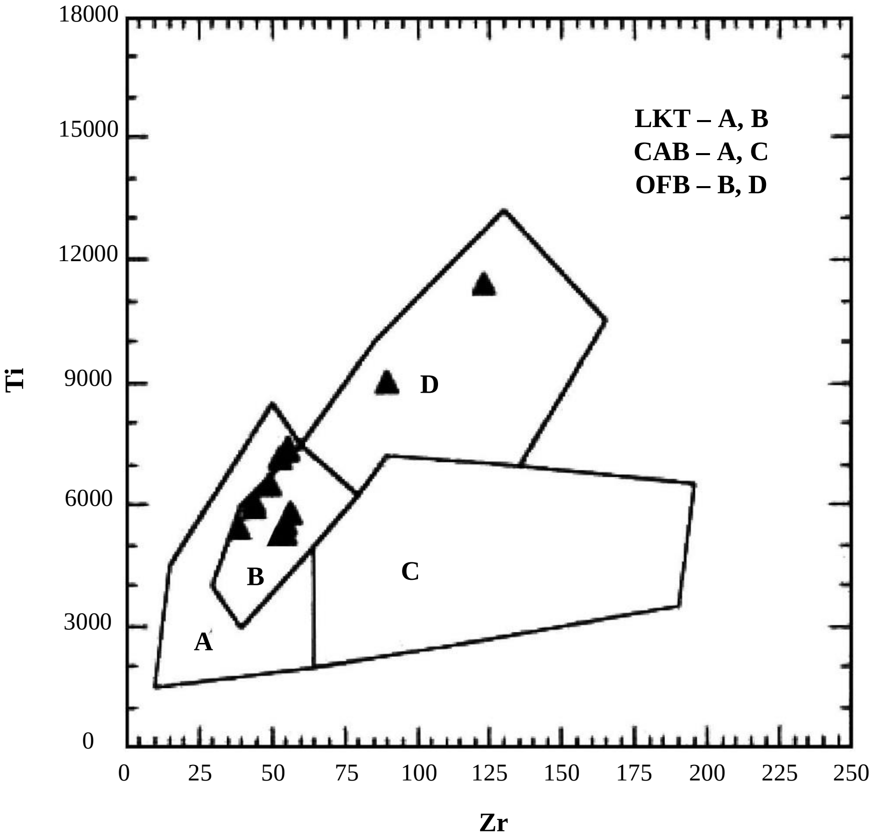


Figure 6. Ti-Zr discriminant diagram after Pearce and Cann (1973)

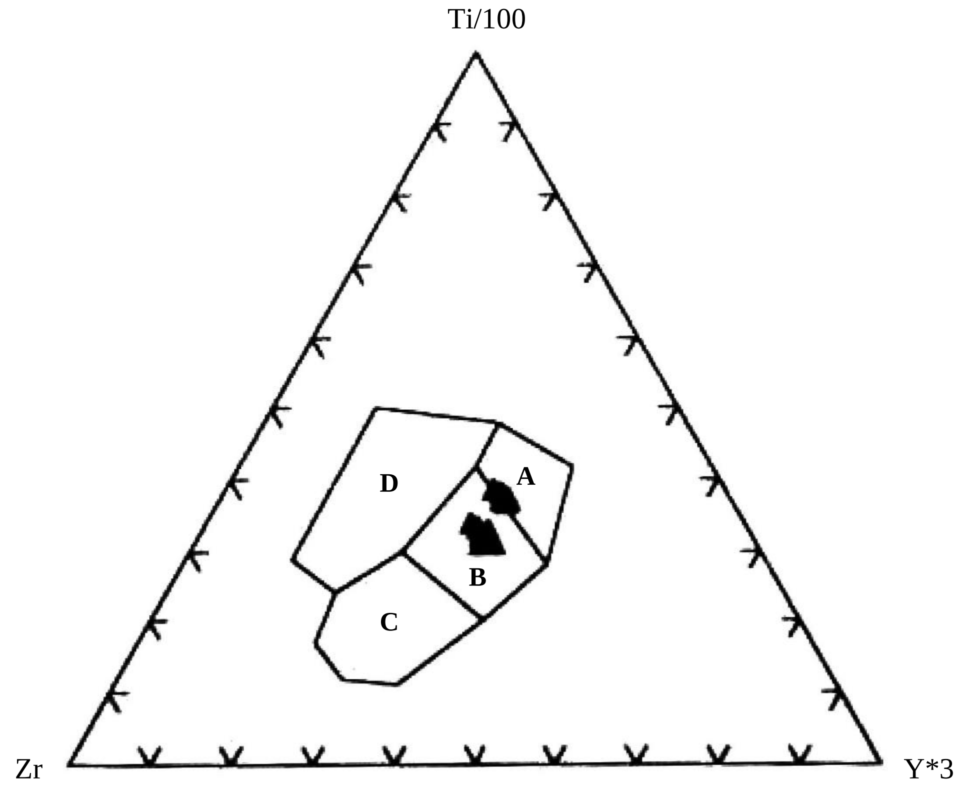


Figure 7. Ti-Zr-Y discriminant diagram after Pearce and Cann (1973). Fields are in Figure 6

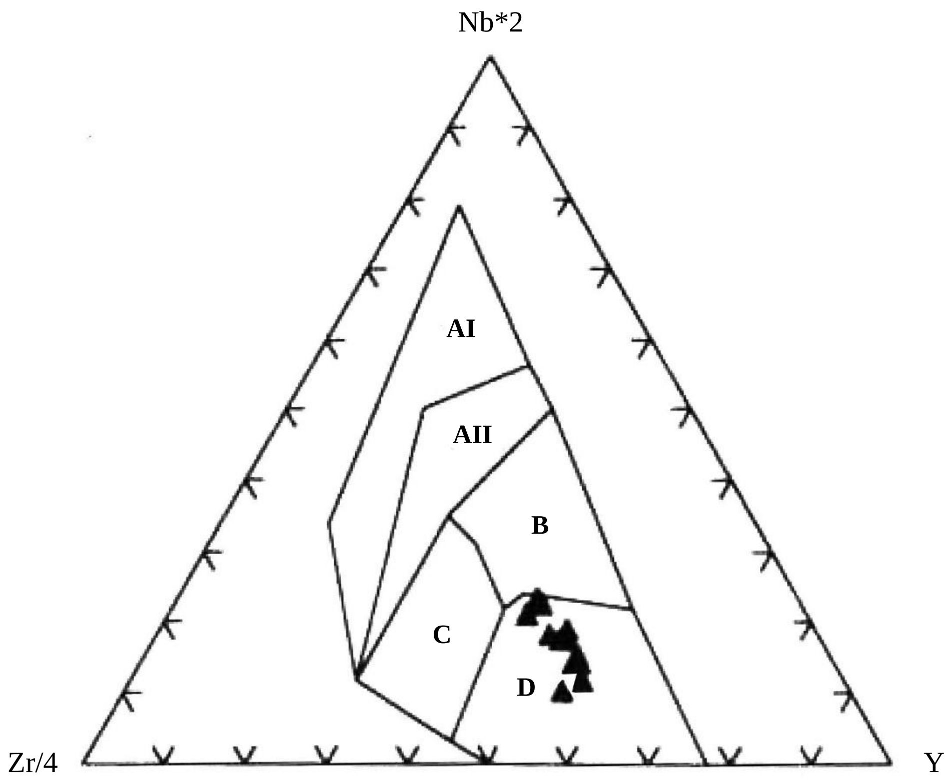


Figure 8. Nb-Zr-Y discriminant diagram after Meschede (1986). Field D: N-type MORB and island arc basalts

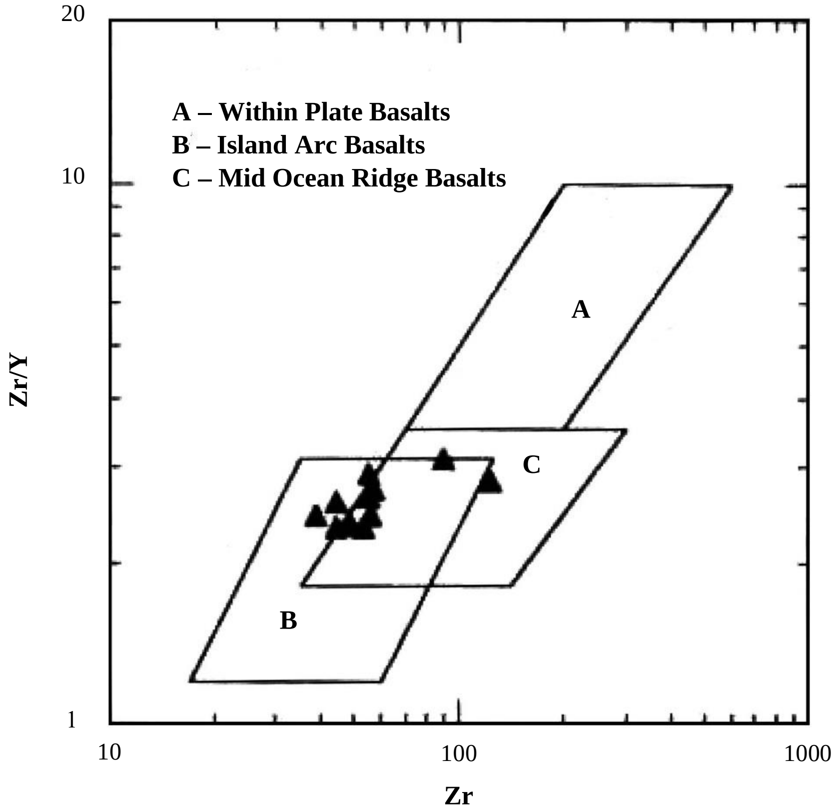


Figure 9. Zr-Zr/Y discriminant diagram after Pearce and Norry (1979)

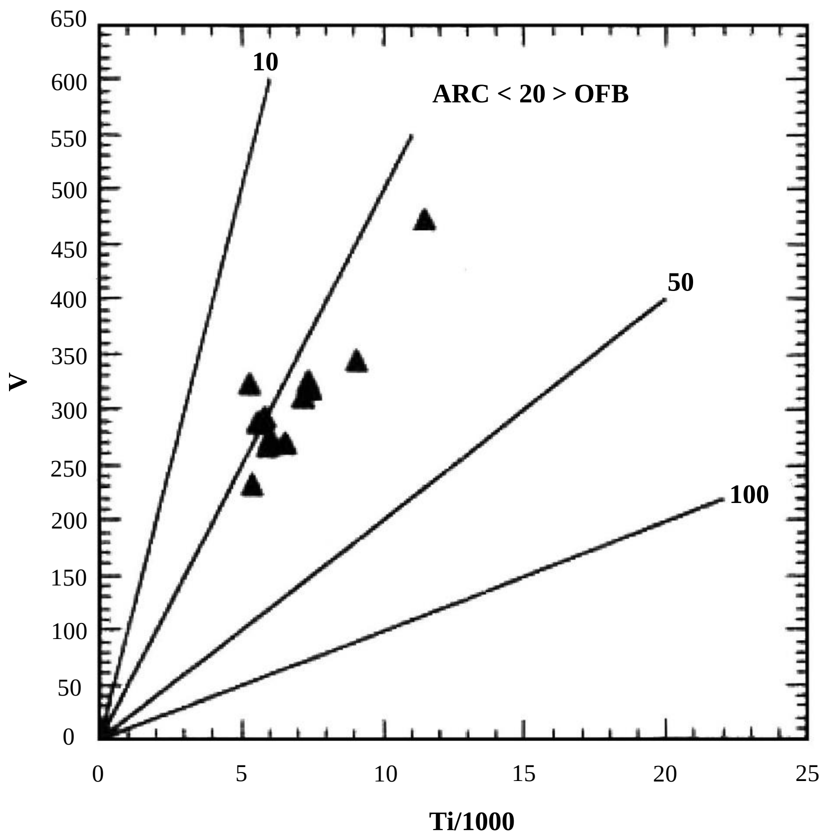


Figure 10. Ti-V discriminant diagram after Shervais (1982)

4.3.4 The Pallatanga Unit in the south-west of the area

The unit is well-exposed along the main road to the west of San Felipe de Molleturo, between [6708-97018] and [6711-97047]. In the western part of this section the basalts are faulted against and tectonically interleaved with sediments from the Yunguilla Unit. At the eastern end of the section, they are strongly sheared and overlain by undeformed volcaniclastic rocks of the Río Blanco Formation of the Saraguro Group. For the most part the road section consists of strongly sheared and hornfelses basalts. They are extremely hard, dark green to almost black rocks which have a vitreous or silicified appearance. Chemical analysis of several samples (PND-1441, PND-1508) from this section indicates that despite their appearance the basalts are not silicified. Because of the shearing and hornfelsing it is difficult to identify these rocks in many of the exposures, although less-sheared relicts display very fine subophitic basaltic textures. In thin section the rocks exhibit cataclastic fabrics, consisting of relict lenses of granulated and broken fine-grained subophitic and variolitic basalt enclosed within highly sheared-mylonitic chloritic matrices.

4.3.5 Petrography and chemical composition of the basalts

In thin section the basalts exhibit variolitic and subophitic textures. Evidence of quenching is common with the development of sheaf-like aggregates of long, curved, hollow plagioclase crystals with interstitial chloritised glass and finely granular clinopyroxene.

Chemical analyses of 12 basalt samples from the unit are presented in Table 1. These were collected from localities distributed along the entire length of the basalt belt between the Pallatanga area in the north and the Molleturo area in the south. In addition, Lebrat (1985) presented 6 analyses of basalts from the mapped area which are here included in the Pallatanga Unit. The data of Lebrat contain analyses of selected rare earth elements (REE).

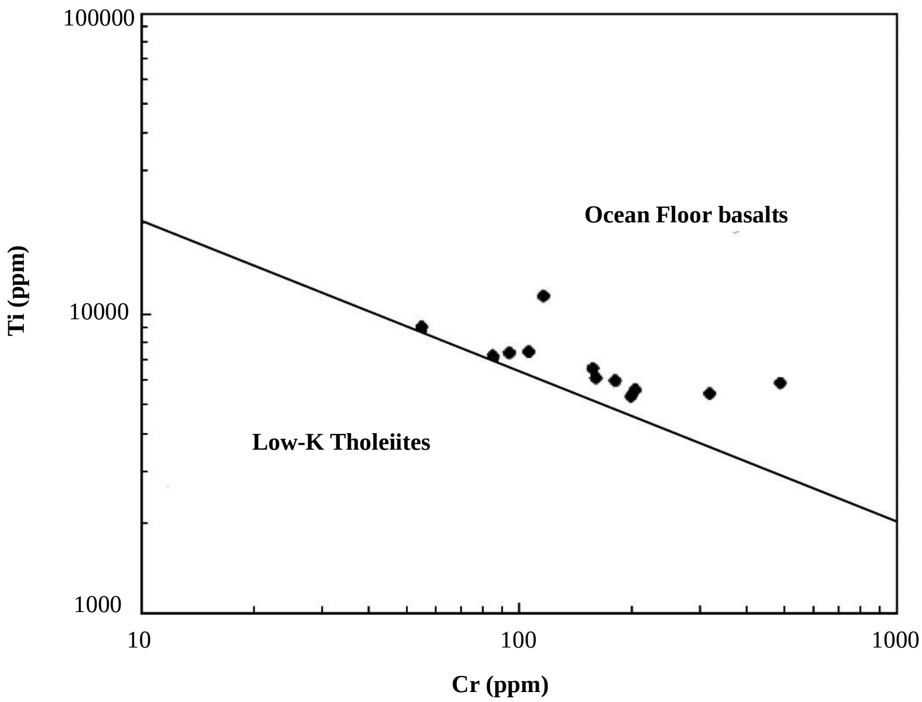


Figure 11. Cr-Ti trace element discrimination plot for basalts of the Pallatanga Unit. Fields from Pearce (1975)

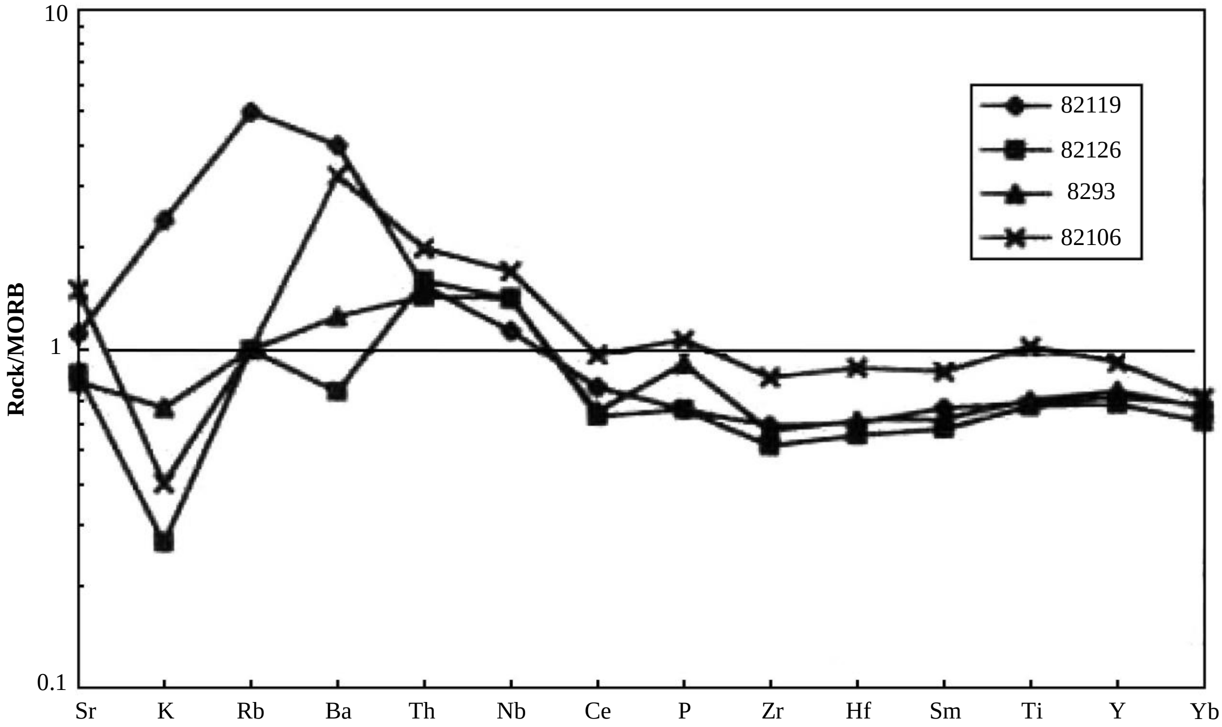


Figure 12. MORB-normalised trace element concentrations of basalt samples from the Pallatanga Unit. Analyses taken from Lebrat (1985). MORB-normalising values from Pearce (1983)

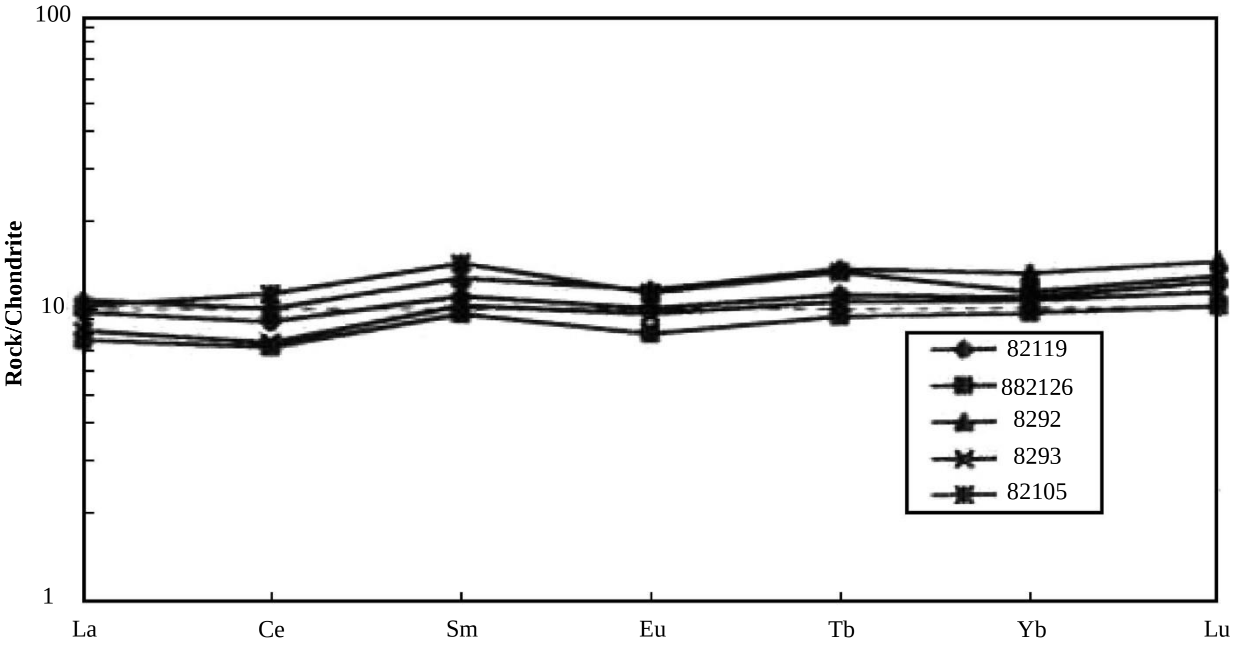


Figure 13. Chondrite normalised rare earth element distribution patterns for basalts from the Pallatanga Unit. Analyses from Lebrat (1985). Chondrite normalising values from Nakamura (1974)

Table 1. Chemical analyses of basalts from the Pallatanga Unit

Sample	**PND-196**	**PND-198**	**PND-199**	**PND-208**	**PND-224**	**PND-225**	**PND-226**	**PND-905A**	**PND-1441**	**PND-1476**	**PND-1482**	**PND-1508**
SiO_2	49.39	49.87	49.93	49.59	48.81	49.64	48.72	49.37	49.87	50.33	48.14	49.11
TiO_2	0.99	1.01	1.23	1.09	0.90	1.20	1.24	0.88	1.51	0.93	1.91	0.97
Al_2O_3	13.67	13.72	13.32	14.11	14.07	13.25	13.47	13.93	13.97	14.54	13.79	13.27
Fe_2O_3	11.53	11.87	13.48	11.49	10.58	13.40	13.45	11.09	13.49	11.28	15.01	11.26
MnO	0.19	0.18	0.21	0.17	0.17	0.21	0.19	0.18	0.21	0.18	0.21	0.18
MgO	7.47	7.50	6.82	7.44	8.28	6.96	7.19	7.77	7.09	8.13	5.68	10.16
CaO	10.90	10.02	8.84	8.99	12.09	10.31	9.72	10.62	9.50	10.40	11.10	12.80
Na_2O	2.58	2.29	3.26	3.57	2.63	2.37	2.43	2.10	2.59	2.24	1.79	1.58
K_2O	0.09	0.29	0.15	0.48	0.11	0.14	0.11	0.18	0.23	0.34	0.22	0.07
P_2O_5	0.07	0.07	0.09	0.07	0.06	0.08	0.09	0.08	0.13	0.08	0.18	0.08
LOI	2.97	2.98	2.56	2.22	1.82	2.01	2.43	3.26	1.81	1.47	1.63	0.54
TOTAL	**99.85**	**99.80**	**99.89**	**99.22**	**99.52**	**99.57**	**99.04**	**99.46**	**100.4**	**99.92**	**99.66**	**100.02**
Ba	-	21	-	-	-	-	-	50	28	55	20	57
Ce	8	9	10	9	8	12	12	14	10	16	55	35
Co	42	42	45	42	41	43	44	53	57	45	66	53
Cr	179	159	94	156	319	85	106	197	55	202	116	490
Cs	-	-	-	-	-	-	-	<2	2	2	<2	<2
Hf	<2	<2	<2	<2	<2	<2	<2	7	7	3	5	4
La	<2	7	6	4	<2	4	5	<2	<2	6	7	<2
Nb	3	2	4	3	3	3	3	2	7	5	11	4
Nd	-	-	-	-	-	-	-	7	11	9	23	11
Ni	81	77	73	87	103	66	79	104	63	82	75	142
Rb	1	5	4	7	1	2	2	2	6	4	2	2
Sc	36	37	38	35	35	39	21	49	46	42	45	51
Sm	-	-	-	-	-	-	-	4	<3	<3	<3	6
Sr	65	101	100	146	122	93	90	130	116	173	107	114
Ta	-	-	-	-	-	-	-	<3	<3	<3	<3	<3
Th	<1	<1	<1	<1	<1	<1	<1	2	1	1	1	1
U	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V	268	326	326	270	234	312	319	325	346	289	473	293
Y	17	23	23	21	16	23	23	21	29	19	44	21
Zr	44	56	56	49	39	53	56	55	90	55	123	57

A number of trace element discrimination techniques have been used to try to characterise the tectonic setting of the basalts of the Pallatanga Unit (Figures 5 to 14). The trace element discrimination diagrams suggest affinities with ocean floor basalts, with a few samples tending to plot in the fields overlapping with those of island arc basalts. Ti and Cr concentrations are relatively high for island arc basalts, and in the Ti vs Cr plot of Figure 11 all the samples fall within the ocean floor basalt field defined by Pearce (1975). These trace element discrimination diagrams therefore suggest that the basalts of the Pallatanga Unit are of MORB origin.

The chondrite-normalised REE data of Lebrat are plotted in Figure 13. This Figure shows slightly enriched but flat patterns typical of N-type MORB. Similarly, the MORB-normalised trace element data of Lebrat are plotted in Figure 12. These show relatively flat patterns with rock/MORB trace element ratios of near unity, which are compatible with MORB-type basalts. In two of the samples however, the large ion lithophile elements (LIL) Ba, Rb and K show enrichment relative to typical MORB compositions. This could be due to metasomatic effects. Similar patterns are seen in the samples collected and analysed by the current project (Figure 14), although these show almost flat MORB-like patterns without LIL-element enrichments.

The slight enrichment in Th relative to MORB compositions seen in Figure 14 is almost certainly a spurious artifact of the XRF analytical method, which is of insufficient precision at low levels for the analysis of this element. Of further significance, the trace element patterns of Figures 12 and 14 do not show depletions relative to MORB in the high field strength elements (HFS) Nb, Zr and Hf, which are so characteristic of destructive plate margin calc-alkaline and low-K tholeiitic volcanic rocks (c.f. Pearce, 1975).

In conclusion, the trace element analyses of basalts from the Pallatanga Unit strongly suggest an ocean floor tectonic environment.

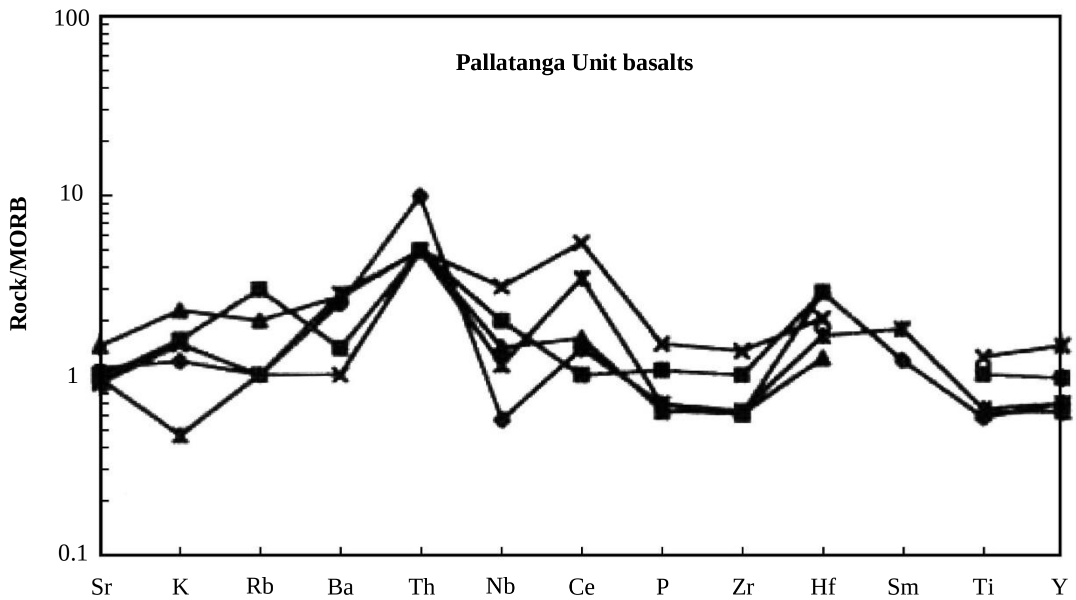


Figure 14. MORB-normalised trace element plot of basalt lavas from the Pallatanga Unit. Samples collected during the current project. Normalising values from Pearce (1983)

4.3.6 Summary and discussion of the Pallatanga Unit

Within the area the Pallatanga Unit consists overwhelmingly of massive and pillowed tholeiitic basalts, with ocean floor basalt trace element characteristics. Minor amounts of hyaloclastite and rare gabbros also occur. The age of the unit is unknown, but could be Middle Cretaceous.

The basalts are faulted against metamorphic rocks to the east and near the contact are highly sheared. The juxtaposition of sheared oceanic basalts against continental metamorphic rocks implies an accretion event, the suture of which is marked by the Bulubulu Fault system. The age of the accretion is uncertain, but several lines of indirect evidence suggest a Campanian age (see Section 8).

4.4 Yunguilla Unit (K_Y)

The Yunguilla Unit is composed essentially of thin bedded siltstones, mudstones and fine sandstones, with intraformational breccio-conglomerates and local occurrences of basic tuffs and tuffaceous sandstones.

The unit occurs in three relatively small, widely separated areas within the western foothills of the cordillera. It crops out near the northern margin of the area, in a faulted belt that extends north-eastwards from San Francisco de Multitud [7230-97671] into the Pallatanga area of the adjacent geological map. In the central western foothills, it occurs in a NE-trending belt that extends to either side of the Cuenca-Jesús María road, approximately between the Estero Tres Ranchos [6785-97161] and the Río Guarumales [6652-97040]. The third area occurs immediately to the west of Carmen de Pijilí, where strongly hornfelsed sedimentary rocks have been tentatively assigned to the unit.

4.4.1 Stratigraphical relationships and age of the Yunguilla Unit

Within the mapped area the Yunguilla Unit is everywhere in faulted contact with, and in places tectonically interleaved with sheared basalts of the Pallatanga Unit. This is well-displayed for example along the main Cuenca-Jesús María road section to the west of [6711-97047]. Together with the basalts of the Pallatanga Unit, the Yunguilla Unit occupies a structural position to the north-west of the Bulubulu Fault system and to the south-east of the Angamarca Group. Where the unit is juxtaposed against the Angamarca Group the contact is faulted.

No evidence has been obtained from the mapped area for the age of the Yunguilla Unit. Foraminifera from the type Yunguilla area near Nono to the north-west of Quito indicate a Maastrichtian age (Hughes et al., 1997). Foraminiferal evidence from the unit a short distance to the north of the mapped area, near Pallatanga, also indicates a Maastrichtian age (Wilkinson, 1996; McCourt et al., 1997).

4.4.2 Lithological description of the Yunguilla Unit

The principal lithologies of the unit are thin bedded siltstones, mudstones and sandstones which typically weather to a dark ochreous brown colour. Bedding is rhythmic, with beds of very fine sandstone and laminated siltstone of the order of 5-15 cm alternating with thin mudstone partings. The sandstones are generally very fine grained and grey to blue-grey in colour when fresh. They are composed of well-sorted angular to subangular grains of feldspar, quartz and traces of ferromagnesian minerals. Grains of muscovite also occur but are not common, although in rare cases muscovite is present in sufficient quantity in hand specimens to merit the term micaceous sandstone. Examination of the thin section indicates the occurrence of strained quartz, which together with the presence of muscovite is taken as evidence for a metamorphic source. The siltstones are dark grey and laminated, and the mudstones are dark grey to black and siliceous. These thin bedded sandstones, siltstones and mudstones are interpreted as turbidites, which mainly display divisions T_{bcd}, although coarser, slightly thicker (20-30 cm) graded sandstone beds corresponding to division T_a also occur but are less common.

Evidence of soft sediment deformation is common within these rhythmically bedded rocks and is an almost diagnostic feature of the Yunguilla Unit. This takes the form of chaotic, disharmonic folds and slump structures, and sedimentary mélanges. Spectacular, large-scale soft sediment folding is well-displayed at a number of localities along the Cuenca-Jesús María road, as for example between [6717-97057] and [6715-97063]. Several roadside exposures in the north of the area around San Francisco de Multitud exhibit chaotically mixed sandstones, siltstones and mudstones, which are interpreted as intraformational mélanges.

Additional lithologies occur within the area which have not been described from the unit elsewhere. These include intraformational breccio-conglomerates, basic tuffs and tuffaceous sandstones. Thick, massive, intraformational mass-flow breccio-conglomerates are common within the thin-bedded sequences along the Cuenca-Jesús María road section, and are particularly well-developed on either side of the bridge over the Río Pauji [6725-97053]. They consist mainly of rounded rip-up clasts of black cherty mudstone supported in siltstone-sandstone and tuffaceous matrices. Basaltic volcanic sandstones, tuffaceous sandstones and possibly reworked hyaloclastites also occur within the road section farther to the west between [6727-97078] and [6721-97098]. A section examined along the Río de Piedras between [6775-97145] and [6789-97120] exposes dark grey bedded siltstones, mudstones and fine micaceous sandstones with intercalations of fine basaltic sandstones and intraformational mass-flow breccio-conglomerates.

Massive quartzitic sandstones with rip-up clasts of black siliceous mudstone are also present in the Cuenca-Jesús María road section between [6726-97080] and [6724-97094]. These have been hornfelsed and silicified, and at many exposures resemble cryptocrystalline rhyolites. The presence of rip-up clasts however indicates a sedimentary origin, and thin section examination of less altered samples at [6725-97082] confirmed these rocks to be fine-grained, mature, finely planar-bedded and cross-bedded quartzo-feldspathic sandstones which are carbonated.

In the south-west near Carmen de Pijilí, a small area of faulted and strongly hornfelsed sedimentary rocks occurs. These are exposed along the road from San Carlos to Carmen de Pijilí. They are difficult rocks to identify in the field because of strong hornfelsing, but fine quartzo-feldspathic sandstones have been identified in thin section, some of which contain grains of muscovite. Basaltic tuffs and volcanic sandstones also occur near the old mine workings at [6615-96733]. These rocks have been tentatively mapped as Yunguilla Unit, partly because they resemble the basic volcaniclastic lithologies seen elsewhere in the unit to the north (although no thin bedded turbiditic rocks have been recognised in this area) and partly because of their structural position and close association with basalts of the Pallatanga Unit.

4.4.3 Summary and interpretation of the Yunguilla Unit

The Yunguilla Unit consists essentially of thin bedded turbidites of Maastrichtian age, which are tectonically interleaved with basalts of the Pallatanga Unit. They occur in a structurally controlled belt, bounded by the Bulubulu Fault to the south-east and by the Multitud-Cañi fault system to the north-west.

The generally thin bedded and fine-grained nature of the turbidites suggests deposition within a distal fan environment, as interpreted by Hughes and Bermúdez (1997) for the unit in the Quito region. The turbidites were affected by mass-movement and soft sediment deformation and were reworked by mass-flows to produce intraformational breccio-conglomerates.

Petrographic evidence, in the form of strained quartz grains and the presence of muscovite suggests derivation of some of the detritus from a metamorphic source area. The rare occurrence of mature quartz conglomerates and quartzitic sandstones also conforms to this supposition. The presence of reworked basaltic tuffs, tuffaceous sandstones and hyaloclastic material also indicates derivation from a basaltic volcanic source which may have been active at the time of deposition.

4.5 Macuchi Unit (PcE_M)

The Macuchi Unit is composed of subaqueously deposited volcaniclastic rocks and lavas of basaltic and andesitic composition, which occur in three fault-bounded blocks in the north-west of the area.

The smallest and southernmost fault block is situated in the foothills to the east of La Troncal. A second block occurs between the Río Chicales and the Río Chimbo, where it forms the prominent mountain of Cerro Cutuguay [7046-97496]. The third and most extensive outcrop of the unit underlies all the ground to the north-west of the Río Chimbo and extends northwards into the area of the adjacent map sheet.

4.5.1 Stratigraphical relationships and age of the Macuchi Unit

The Macuchi Unit is bounded along its south-eastern margin by the Chimbo-Cañi and Multitud fault systems, which everywhere bring it into juxtaposition with turbiditic sedimentary rocks of the Angamarca Group. To the west and north-west the unit passes beneath alluvial deposits of the coastal plain.

No information has been obtained from the mapped area on the stratigraphical position and age of the Macuchi Unit. The type area of the unit occurs around the mining settlement of Macuchi, situated in the sector of the cordillera between 1°S-0°, which has been mapped during the current project by Hughes and Bermúdez (1997). Egüez (1986) reported Early to Middle Eocene radiolaria and Early Eocene foraminifera from sedimentary rocks of the unit a few kilometres to the west of the type area. In addition, Egüez (*op. cit.*) also reported two K-Ar whole-rock ages of 41.6 ± 2.1 and 35.8 ± 1.8 Ma (Middle to Late Eocene) from basaltic andesite intrusions in the same area. From this evidence, at least part of the Macuchi Unit is of Early to Middle Eocene age, although Hughes and Bermúdez (1997) suggest that older parts of the sequence could conceivably be of Palaeocene age, but this cannot be proven.

4.5.2 The Macuchi Unit in the foothills near La Troncal

In the area to the east of La Troncal the unit has been examined in sections along the Estero Bucarcar [6915-97323], the Estero Playa Seca [6915-97359] and the track between San Isidro [6957-97417] and San Pascual [6958-97385].

Basaltic tuffs, microbreccias, tuffaceous sandstones and lavas with rudimentary pillows outcrop in the Estero Bucarcar and Estero Playa Seca. In thin section the lavas are seen to be very fine-grained basalts with variolitic textures and fine amygdales. The tuffs and microbreccias have vitroclastic textures, consisting of shards and fine scoria lapilli composed of pale brown glass (sideromelane) set within fine matrices altered to assemblages of chlorite, epidote, calcite, clays and oxides.

Both rivers contain abundant boulders of a distinctive type of breccia composed of red-brown and bright green angular clasts of very fine-grained and glassy basaltic lava set within fine red-brown tuffaceous matrices. These are mainly microbreccias which exhibit both clast-supported and matrix-supported fabrics. A high proportion of the clasts are splinter-like shards with curvilinear surfaces, typical of hyaloclastite fragments formed by the subaqueous quenching of lavas. Ragged shaped vesicular clasts also occur and may be indicative of weakly explosive disruption of the parental lavas. Although these breccias have not been seen *in situ*, their texture is sufficiently distinctive to classify them as hyaloclastites.

In the San Isidro-San Pascual area the unit consists of a thick sequence of basaltic andesite breccias with occurrences of lava. These are exposed along the track between San Isidro and San Pascua. At the northern end of the track, near San Isidro, vesicular and amygdaloidal feldspar-phyric andesite lavas are exposed. Southwards the lavas pass up into a thick and monotonous sequence of basaltic andesite hyaloclastite breccias and microbreccias. These are weathered, but where fresh they are seen to be identical to the hyaloclastic breccias found as floats within the esteros Bucarcar and Playa Seca to the west (see previous paragraph). They are composed mainly of red-brown and green, angular shard-like clasts of lava with curvilinear surfaces, which commonly have bleached rinds. In a small tributary quebrada of the Río Piedritas at [6952-97375] the breccias are seen in faulted contact with highly sheared mudstones and siltstones of the Angamarca Group.

4.5.3 The Macuchi Unit around Cerro Cutuguay

Basaltic and basaltic andesite lavas, tuffs and tuffaceous sandstones are poorly exposed along the road on the south-east side of Cerro Cutuguay, between the bridge across the Río Chicales [7034-97456] and Cutuguay Centro [7074-97480]. The thin section examination indicates that the lavas are fine to medium grained with variolitic and pilotaxitic textures, and are altered to secondary mineral assemblages of chlorite, actinolite, epidote, calcite and zeolites. The road crosses several quebradas which drain the south-eastern flanks of Cerro Cutuguay. Boulders within these quebradas indicate a source upstream composed of basaltic lavas, tuffs and a high proportion of hyaloclastic breccias with distinctive red and green shard-like clasts of identical appearance to the breccias from the La Troncal area (described in the previous section). Boulders of microgabbro (dolerite) are also common.

The railway line between Hacienda Elvira [70705-97550] and [7078-97534] provides a section almost perpendicular to strike. This exposes steeply dipping and weathered basaltic-basaltic andesite breccias, interstratified with basaltic tuffs and volcanic sandstones. At least some of these volcaniclastic rocks are reworked hyaloclastites.

4.5.4 The Macuchi Unit to the north-west of the Río Chimbo

The large area of the Macuchi Unit to the north-west of the Río Chimbo was not investigated in detail due to lack of time. Sections were examined along the Chimbo Valley and along a road traverse through the central part of the area between San José de la Comuna [7120-97775] and La Miran [7095-97680]. In addition, the project's geochemical sampling teams collected a large number of rock samples from this block of ground, some of which were examined in thin section.

A typical and instructive section is exposed around the water-works immediately to the west of Cumandá [7086-97568]. Here thick-bedded volcanic sandstones, secondary tuffs and mass-flow breccias and breccio-conglomerates of broadly andesitic composition outcrop. The sandstones and tuffs are coarse-grained and contain abundant plagioclase crystals. Some beds are graded. The breccias and breccio-conglomerates consist of subangular blocks of basaltic lava up to 0.5 m in size, including pillow fragments, supported in crystal-rich tuffaceous matrices.

The road section between San José de la Comuna and La Miran exposes a stratified sequence of pale grey-green andesitic crystal tuffs, volcanic sandstones, siltstones and debris-flow breccias with minor occurrences of lava. Many of the tuffs are reworked and together with the sandstones and siltstones form thin- to thick-bedded sequences which exhibit graded bedding, plane lamination and low-angle cross-bedding. These are interpreted as a turbidite sequence (T_{abc}).

Rock samples collected throughout the area to the north-west of the Chimbo by the geochemical sampling teams include similar lithologies to those from the sections described above. They include a high proportion of volcaniclastic rocks, including tuffs, hyaloclastites, volcanic sandstones and lavas. The tuffs and hyaloclastites display excellent vitroclastic textures in thin section, with relatively fresh glass shards and expanded glassy scoria lapilli still preserved as sideromelane. Even the reworked tuffs and volcanic sandstones contain a high proportion of relatively fresh glass shards. The general composition of these volcaniclastic rocks appears to be basaltic to andesitic, although more acid compositions also occur, as for example dacitic tuffs in the Río Atio at [7038-97718].

Lavas interstratified within the volcaniclastic sequence in the area to the north-west of the Chimbo are mainly fine-grained aphanitic and microporphyritic basalts and basaltic andesites, but also include porphyritic andesites, some of which contain hornblende phenocrysts. Vesicular and amygdaloidal lavas are common, and well-developed pillow lavas are exposed in the Chimbo Valley between [7197-97724] and [7202-97714]. Small bodies of gabbro and microgabbro also intrude the unit, as for example in the Chimbo Valley around El Cadial [7185-97725].

4.5.5 Composition of the Macuchi Unit

No chemical analyses have been obtained from the Macuchi Unit within the area of the map, but based on general appearance and petrographic examination the lavas appear to be mainly basalts and basaltic andesites with relatively minor occurrences of andesite. The tuffs and reworked volcaniclastic rocks in the area to the north-west of the Chimbo are more andesitic in appearance than the lavas, although in thin section much of the glass within these rocks is pale brown and appears to be basaltic.

Hughes and Bermúdez (1997) report 15 chemical analyses of lavas and breccia clasts from the Macuchi Unit in the area between 1°S-0°. These range in composition from basalt to high-silica andesite. Trace element discriminant analysis suggests a transitional tholeiitic to calc-alkaline island arc tectonic setting, although MORB-like signatures are displayed by a few samples.

4.5.6 Summary and discussion of the Macuchi Unit

The Macuchi Unit consists of subaqueously deposited basaltic and andesitic volcaniclastic rocks, lavas and intrusions of Early to Middle Eocene age and possibly older. The south-eastern margin of the unit is bounded by the Chimbo-Cañi and Multitud fault systems which everywhere juxtapose it against the Angamarca Group.

The dominant lithologies are volcanic sandstones, primary and reworked basaltic tuffs, breccias and hyaloclastites. Basaltic and andesitic lavas also occur, including pillow lavas and pillow breccias. The rocks show extensive evidence of reworking and emplacement by mass-flow processes, including debris flows and turbidity currents. The abundance of primary tuffs with good vitroclastic textures and expanded scoria lapilli suggests eruption within shallow water or even subaerial environments. Shallow water environments are also suggested by the strongly vesicular nature of some of the lavas.

Chemical analyses of lavas within the unit to the north of the mapped area (Hughes and Bermúdez, 1997) indicate basaltic and andesitic compositions of tholeiitic to calc-alkaline affinity with island arc trace element characteristics. Within the mapped area, the large volumes of basaltic and basaltic andesitic rocks in association with lesser volumes of andesitic rocks and minor occurrences of dacitic tuffs are consistent with an immature island arc of transitional tholeiitic to calc-alkaline character.

In conclusion, the weight of the evidence supports the view that the Macuchi Unit formed within an intra-oceanic island arc. All of the unit appears to have accumulated in a submarine environment. Lavas were clearly erupted locally, although much of the volcaniclastic material was brought into the depositional environment by mass-flow processes. There is considerable evidence however, that much of the pyroclastic material and some of the lavas were erupted in shallow water or conceivably in a subaerial environment.

4.6 Angamarca Group (PcE_{Ag})

The Angamarca Group of the mapped area consists of well-bedded turbiditic sandstones, siltstones and mudstones, with intercalations of dacitic tuff.

The rocks of the group crop out in the western foothills in a fault-bounded belt which extends south-westwards from Pallatanga to the Cochancay area [6895-9275]. Here it passes beneath the alluvium of the coastal plain, but reappears farther south-west in the foothills near Naranjal.

4.6.1 Stratigraphical relationships and age of the Angamarca Group

Within the mapped area the Angamarca Group occupies a structural position between the Pallatanga Unit to the south-east and the Macuchi Unit to the north-west. On its south-eastern margin the group is faulted against the Pallatanga Unit along the Multitud Fault, and on its north-western margin against the Macuchi Unit along the Chimbo-Cañi Fault system.

The Angamarca Group is a newly defined stratigraphical unit which is interpreted as a coarsening upwards siliciclastic basin-fill sequence (Hughes and Bermúdez, 1997). Palaeontological evidence from the sector of the cordillera between 0°-1°S indicates a Palaeocene to Eocene age for the group (Hughes and Bermúdez, *op. cit.*).

Within the area covered by this report, a fission track date of 37.8 ± 3.5 Ma was obtained from a dacitic ash-flow tuff intercalated within turbiditic sediments of the Group at Guamampata [7215-97692]. This is equivalent to a Late Eocene age, in keeping with the palaeontological evidence obtained from the group elsewhere.

Up to five formations have been mapped within the Group farther north (Hughes and Bermúdez, *op. cit.*; and McCourt et al., 1997), but within the area of this report only two units have been recognised, namely the Apagua Formation and the undifferentiated Angamarca Group.

4.6.2 Apagua Formation (PcE_{Aga})

The Apagua Formation only occurs in the extreme north, in a faulted wedge along the west side of the Río Coco [7240-97770]. Here it consists of thin- to medium-bedded fine- to medium-grained turbiditic sandstones intercalated with black siltstones and silicified mudstones.

The sandstones are fine-grained, well-sorted and rich in quartz and feldspar, but contain few lithic grains, only traces of mica and virtually no mafic minerals. They are graded and exhibit weakly developed sole structures. Less commonly they are cross-laminated.

No evidence has been obtained for the age of the formation within the mapped area. The type area for the Apagua Formation occurs near Apagua, which is located along the Latacunga to La Maná road (Hughes and Bermúdez, 1997). The formation is known to have a lower age limit equivalent to the Middle Palaeocene (Wilkinson, 1997) and the youngest part is post Middle Eocene (Hughes and Bermúdez, *op. cit.*).

4.6.3 Undifferentiated Angamarca Group (PcE_{Ag})

Rocks which have been mapped as undifferentiated Angamarca Group consist essentially of turbiditic sandstones, siltstones and mudstones similar to those of the Apagua Formation, but with intercalations of intermediate tuffs. It is uncertain how these rocks correlate with the other formations of the Angamarca Group in other parts of the cordillera, although the presence of considerable amounts of tuff is a significant variation not seen in the group elsewhere.

The undifferentiated rocks of the Angamarca Group have been mapped in two main areas. In the north-west they form a continuous belt between Pallatanga, Cumandá and Cochancay, and in the south-west they outcrop in the foothills of the cordillera to the east of Naranjal.

The group is well-exposed along the Cumandá-Pallatanga road between [7137-97587] and [7239-97689], and along the railway line to the south of Cumandá between [7078-97532] and [7082-97523]. Here the succession strikes NE and generally dips steeply to the SE, although locally the strata are vertical or show reversals in dip. The sequence consists mainly of thin- to medium-bedded fine- to medium-grained turbiditic sandstones intercalated with black siltstones and mudstones, similar in appearance to those of the Apagua Formation. The sandstones are mainly well-sorted and rich in quartz and feldspar grains, but in contrast to those of the Apagua Formation they are calcareous. They exhibit graded beds with weakly developed basal loading structures, plane parallel lamination, low-angle cross-bedding and less commonly convolute bedding (T_{abc}). The finer laminated sandstones show grading into overlying siltstone bands (T_d).

Massive tuffs of mainly dacitic composition are interbedded within the turbiditic sediments. These can be seen for example in the railway line section at [7078-97529] and in several exposures along the Cumandá-Pallatanga road, for example between [7172-97627] and [7174-97632]. They also outcrop in the Río Piedritas to the south of San Pascual [6958-97385]. They are pale grey-green vitroclastic rocks which contain abundant matrix-supported rip-up clasts of black, silicified mudstone and siltstone derived from the background sediments. Eutaxitic textures occur, although it is uncertain whether this is due to welding or is a texture produced by the flattening of pumice and glass shards as a result of diagenetic alteration and compaction.

The thickest known tuff occurs at the prominent bend in the main road immediately north of Guamampata [7215-97692]. Here a massive, pale grey dacitic ash-flow tuff is intercalated with the turbiditic sediments. It is between 20-30 m thick and contains abundant lithic lapilli and rip-up clasts of sediment reaching more than a metre in size. Shardic textures can be seen in hand specimen and in thin section. Under the hand lens numerous small, very fine-grained, perlitically cracked dacitic or rhyodacitic clasts can be seen. These are interpreted as original obsidian clasts which were perlitically cracked as a result of hydration. The basal contact of this tuff with the underlying turbidites is not exposed, but the top is reworked and shows an upward transition into tuffaceous sandstone with several thin intercalations of siltstone and mudstone, which are in turn overlain conformably by thin- to medium-bedded turbiditic sandstones, siltstones and mudstones representing the background sedimentation. A Late Eocene zircon fission-track age of 37.8 ± 3.5 Ma was obtained from the tuff at this locality.

Thin-bedded sandstones, siltstones and mudstones outcrop in the foothills to the south and east of Naranjal. No evidence for the age of these rocks has been obtained, but they are assigned to the Angamarca Group (undifferentiated) because of their similar lithology and structural position, being situated to the west of the Pallatanga Unit. The main outcrop to the east of Naranjal has only been examined in one section, along the valley of the Río Amazonas, although similar rocks have been observed and sampled elsewhere in this general area by the project's geochemical sampling teams. To the south of Naranjal contact metamorphosed sediments are exposed in two tracks which lead up to the antennae at [6475-96929] and [6486-96945]. Although strongly hornfelsed they appear to consist mainly of sandstones and siltstones, some of which are micaceous.

4.6.4 Summary and discussion of the Angamarca Group

The Angamarca Group consists essentially of thin- to medium-bedded turbiditic sandstones, siltstones and mudstones which occur in a broad fault-bounded belt between the Pallatanga Unit to the south-east and the Macuchi Unit to the north-west.

The Group was defined by Hughes and Bermúdez (1997) who interpret it as a coarsening upwards siliciclastic basin fill sequence of Paleocene to Eocene age.

Dacitic tuffs of Late Eocene age are interbedded with the turbidites. These have not been recognised in the group in other parts of the cordillera. They include primary ash-flow tuffs, reworked tuffs and tuffaceous sandstones that were emplaced by a combination of pyroclastic flow, debris-flow and turbidity-flow. The tuffs are of the same age and similar composition to the ash-flow tuffs of the Ocaña Formation, which outcrops between 5-8 km to the south-east of the Angamarca Group and is the oldest dated unit of the Saraguro Group (Section 4.7). The tuff intercalations are therefore interpreted as pyroclastic flows representing some of the earliest activity of the Saraguro Group, which entered the Angamarca sedimentary basin from the east.

4.7 Saraguro Group

4.7.1 Introduction

The Saraguro Group is here defined as a sequence of intermediate to acid calc-alkaline volcanic rocks of late Middle Eocene to Early Miocene age. The group crops out over a very large part of the southern sector of the Western Cordillera and appears to reach its fullest and most extensive development in the area covered by this report.

A number of earlier workers have used the name Saraguro in connection with various volcanic rock units in southern Ecuador. Kennerley (1973) used the term Saraguro Group for intermediate to acid volcanic rocks near Saraguro, which were of unknown age but assumed to belong to the upper Tertiary. Later Kennerley (1980) renamed these rocks as the Saraguro Formation and assigned them to the Oligocene, whilst Baldock (1982) subsequently reverted to the term Saraguro Group. On the latest edition of the National geological map these rocks are termed Volcánicos Saraguro (BGS-CODIGEM, 1993). These earlier works used the name Saraguro for rocks of a more restricted age range than in the present study, assigning them to the Oligocene on relatively scant evidence. Former surveys and previously published maps have also tended to underestimate the true extent of this volcanic unit, assigning most of the rocks now included in the group to significantly younger units such as the Tarqui Formation (e.g. DGGM, 1980) and Volcánicos Pisayambo (e.g. BGS-CODIGEM, 1993), or to the older Macuchi Formation (e.g. DGGM, 1980 and Egüez et al., 1988).

Table 2. Summary of the main features of the Saraguro Group within the mapped area

Name of unit	Lithologies	Type area-best sections	Stratigraphical relationships	Radiometric dates	Age
Puñay Unit	Andesitic lavas, breccias and sandstones. Red-purple siltstones	Cerro Puñay-Huigra area	Unconformably overlies Ocaña Fm. Unconformably overlain by Turi Fm.		Late Oligocene?-Early Miocene?
Jubones Fm.	Rhyolitic ash-flow tuff. Crystal-rich, strongly welded	Río Minas [6830-96320]	Unconformably overlies Plancharumi Fm. Unconformably overlain by Quimsacocha Fm.	22.76 ± 0.97 Ma 23.0 ± 2.2 Ma	Basal Miocene
Plancharumi Fm.	Rhyolitic ash-flow tuffs, lavas and breccias, fine-ash tuffs, siltstones and sandstones. Lacustrine	Escarpment of Cerro Plancharumi [6990-96737]	Unconformably overlies Soldados Fm. Unconformably overlain by Jubones Fm.	25 ± 1.1 Ma	Late Oligocene
Cerro Caucay Fm.	Rhyolitic ash-flow tuff. Crystal-rich, ultra-welded and rheomorphosed	West of Cañar around Cerro Caucay [7227-97188]	Unconformably overlies Chanlud Fm. Unconformably overlain by Turi Fm.	27.0 ± 1.0 Ma 30.2 ± 1.1 Ma	Latest Early Oligocene-Late Oligocene
Soldados Fm.	Crystal-rich dacitic ash-flow tuffs. Strongly welded	Around Soldados [6965-96741]	Unconformably overlies Río Blanco and Chanlud Fms. Unconformably overlain by Plancharumi Fm.	26.08 ± 0.8 Ma 27.07 ± 0.7 Ma 29.8 ± 1.2 Ma	Late Oligocene
Río Blanco Fm.	Andesitic lavas, tuffs, breccias and sandstones. Some dacitic ash-flow tuffs and lavas	Río Blanco [6819-96883] and the road between [6825-96921] and [6709-97014]	Unconformably overlies Chulo Fm. Unconformably overlain by Soldados Fm. Could be equivalent to Chanlud Fm.		Early Oligocene
Chanlud Fm.	Andesite lavas and breccias, minor dacitic and rhyodacitic lavas	Around Represa Chanlud [7145-96985]	Overlies Tomebamba Unit in places with angular unconformity and in others with a conformable-transitional contact. Unconformably overlain by Soldados and Cerro Caucay Fms.		Early Oligocene
Tomebamba Unit	High-silica andesitic and basic dacitic ash-flow tuffs	South-east Cajas-Tomebamba valley	Unconformably overlies Chulo Unit. Overlain by Chanlud Fm. with transitional and broadly conformable contact, and also unconformable contact	34.1 ± 1.3 Ma	Early Oligocene
Filo Cajas Unit	Dacitic ash-flow tuffs, and lavas	Filo Cajas [6932-96967]	Disconformably overlies Chulo Unit. Unconformably overlain by Chanlud Fm. and Tomebamba Unit		Late Eocene or basal Oligocene
Chulo Unit	Rhyolitic-rhyodacitic ash-flow tuffs, breccias, lavas and lacustrine sediments	Chulo [6980-97003]-Cerro Arquitecto [6943-96928]	Unknown relationship with Ocaña Fm., possibly older. Disconformably overlain by Filo Cajas Unit		Late Eocene or older
Ocaña Fm.	Dacitic ash-flow tuffs. Crystal-rich, strongly welded	Main road between Ocaña [6975-97246] and Javín [7024-97269]	Unconformably overlies basement schists. Unconformably overlain by Tomebamba and Puñay Units	35.9 ± 0.9 Ma 37.0 ± 1.5 Ma 38.6 ± 1.3 Ma	Middle Eocene-Late Eocene

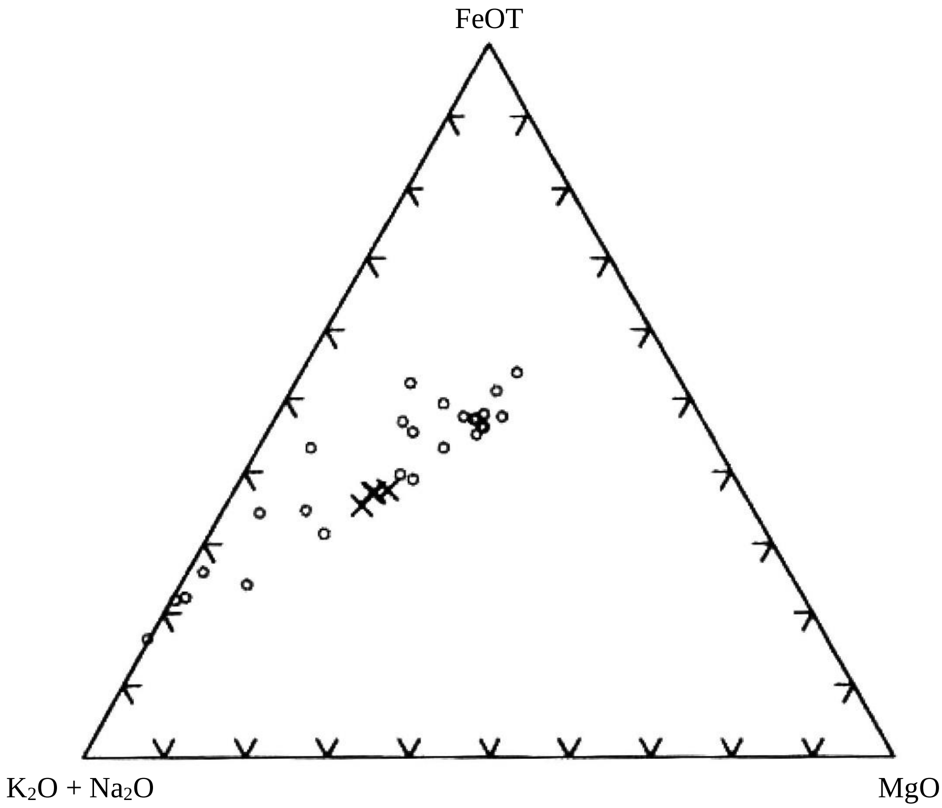


Figure 15. FMA triangular diagram of lava compositions. Open circles Saraguro Group, crosses Cisarán Formation

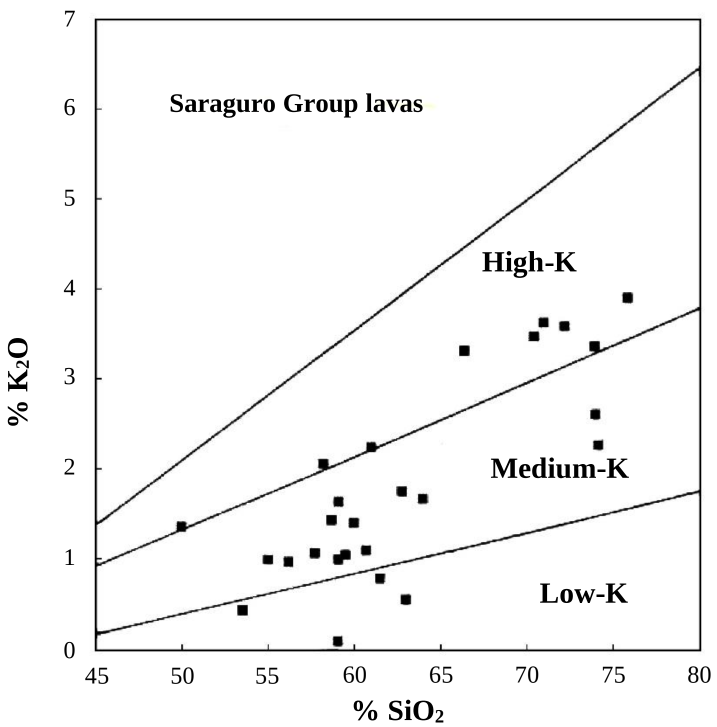


Figure 16. K_2O vs. SiO_2 variation diagram of Saraguro Group lavas. Boundaries of low-, medium- and high-K calc-alkaline fields are taken from Gill (1978)

In the present study this volcanic sequence is formally given Group status. It is very thick and extensive and includes a number of distinctive lithological units which formed over a prolonged period of time. The salient features of these units are summarised in Table 2.

Within the mapped area the Saraguro Group is faulted against, or rests unconformably upon the metamorphic rocks which form the basement of the Western Cordillera to the southeast of the Bulubulu Fault. Along the western margin of the outcrop, rocks of the group also rest unconformably upon, or are faulted against, deformed oceanic basalts of the Pallatanga Unit. The oldest dated unit within the group is the Ocaña Formation, which rests upon metamorphic basement and has yielded several fission-track and radiometric dates, the oldest of which is 38.6 ± 1.3 Ma. The youngest dated unit is in the La Paz Formation, which outcrops just to the south of the mapped area and has yielded a fission track age of 22.5 ± 0.9 Ma (Pratt et al., 1997). Pratt et al. (*op. cit.*) also report several other younger fission-track dates from undifferentiated Saraguro Group rocks in the same area (e.g. 21.5 ± 0.8 and 20.7 ± 2.4 Ma).

The relative ages of the three oldest lithostratigraphical units of the Saraguro Group are uncertain. On the published map the Ocaña Formation has been described as the oldest on the grounds that it has yielded the oldest radiometric dates. However, the Chulo Unit has not been dated and shows no contact relationships with the Ocaña Formation, and could conceivably be older. The only evidence to support such a notion is circumstantial and is based on the fact that there are similarities in appearance, composition and mineralogy between the main dacitic ash-flow tuff of the Ocaña Formation and that of the Filo Cajas Unit which overlies the Chulo Unit. It is therefore possible that the Chulo Unit, which is rhyolitic, is the oldest unit and is post-dated by the dacitic ash-flow tuffs of the Filo Cajas Unit and Ocaña Formation, which could be correlatives of one another.

The group mainly consists of large-scale welded ash-flow tuff units and reworked volcaniclastic rocks. Lavas are also important and include locally developed andesitic, dacitic and rhyolitic domes and flows, as well as a thick sequence of laterally extensive andesites which outcrop over a large area to the north-west and west of Cuenca. The environment of deposition throughout most of the group was subaerial, although waterlain sequences also occur locally. The radiometric dates obtained by the present project indicate that the group formed over a period of about 18 million years, during which time there were episodes of deformation and erosion. Unconformities and non-sequences are therefore common.

The group is of andesitic to rhyolitic composition. Taking the entire Saraguro Group into account, including the area to the south (Pratt et al., 1997), the relative volumes of andesitic, dacitic and rhyolitic compositions are approximately equal. Figure 15 indicates that the lavas of the group have a calc-alkaline trend, and in general they fall in the medium-K and high-K calc-alkaline fields as illustrated in Figure 16.

4.7.2 Ocaña Formation (E_{So})

Dacitic volcaniclastic rocks, consisting predominantly of strongly welded ash-flow tuffs, outcrop along the main La Troncal-Zhud road between Ocaña [6975-97246] and the settlement of Javín [7024-97269]. These are here named the Ocaña Formation. The unit has been mapped north-eastwards to the Huigra area where it passes beneath younger volcanic cover. It extends south-westwards from the Ocaña area, but has not been examined in detail in this ground and has only been identified in sporadic outcrops and in floats within the Río Patul and around San Antonio de Gualleturo.

4.7.2.1 Stratigraphical relationships and age of the Ocaña Formation: The formation is faulted against basalts of the Pallatanga Unit, and it unconformably overlies and is faulted against schists of the metamorphic basement. It is in turn unconformably overlain by the Tomebamba Unit of Early Oligocene age.

Two fission-track dates have been obtained from the Ocaña Formation during the present study. An age of 37.0 ± 1.5 Ma was obtained from a sample (PND-1692) of intensely welded dacitic ash-flow tuff outcropping along the Ocaña-Javín road section at [6998-97252]. An identical ash flow tuff exposed along the El Triunfo-Huigra road at [7164-97692] yielded a similar age of 38.6 ± 1.3 Ma (PND-1698). Egüez et al. (1990) also report a K/Ar of 35.9 ± 0.9 Ma from intermediate volcanic rocks situated to the west of Huigra at [7240-97467], which have been included in the Ocaña Formation by the present study.

These dates indicate an uppermost Middle Eocene to Late Eocene age for the Ocaña Formation.

Although the Ocaña Formation has yielded the oldest radiometric dates of the Saraguro Group, it may not be the oldest lithostratigraphic unit of the Group. The stratigraphical relationships of the formation with the Chulo Unit and Filo Cajas Unit are uncertain. No radiometric dates have been obtained from these latter two units, but on the basis of regional dips of strata it is possible that the Chulo Unit is older than the Ocaña Formation. The main dacitic ash-flow tuff of the Filo Cajas Unit is also lithologically similar to the ash-flow tuff of the Ocaña Formation in the type section, except that it shows evidence of being more proximal to an eruptive source. It is therefore possible that Ocaña Formation is a more distal equivalent of the Filo Cajas Unit, and that both of these units post-date the Chulo Unit.

4.7.2.2 The Ocaña Formation between Ocaña and Javín: The formation is well-exposed along a 5 km stretch of the La Troncal-Suscal road between Ocaña and Javín. A parallel section also occurs a few kilometres to the north along the old road leading westwards from Javín towards La Troncal.

The Ocaña section consists mainly of massive crystal-rich ash-flow tuffs which are strongly welded. In places reworked tuffs, volcanic arenites and mass-flow breccias occur. It is uncertain whether the massive ash-flow tuffs of the section represent a single pyroclastic flow or a number of smaller flows, although a large part of the section does appear to be represented by a single massive unit. The tuffs are dark grey-green and glassy with abundant feldspar and rounded and embayed quartz crystals. Eutaxitic textures are commonly developed and vitroclastic textures can be seen on weathered surfaces. In thin section the tuffs are seen to be intensely welded. Matrices have excellent vitroclastic textures consisting of welded glass shards and deformed pumice lapilli. Accidental lithic clasts ranging up to 20 cm in size are found throughout the tuffs and consist of intermediate lava and more rarely of medium-grained granitoid lithologies. Abundant small clasts of schist also occur near the base of the unit.

Chemical analyses and numerous gamma-ray measurements indicate the rocks of the formation are dacitic. Two analyses of welded tuffs from the Ocaña section are presented in Table 3. When recalculated on a water-free basis these have basic dacite compositions.

At the western end of the Ocaña section the tuffs are faulted against graphitic schists along the Bulubulu Fault. The faulted contact is exposed along the old road at [6975-97259], where both the schists and tuffs are strongly sheared. Although the contact is faulted at this locality, mapping indicates that a short distance to the north-east along the east side of the Bulubulu valley the contact between the schist and the tuffs is probably an unconformity. The unconformity has not been seen, but on the old road section at [7002-97272] an outcrop is exposed near the base of the tuffs. This consists of a strongly welded dacitic ash-flow tuff containing abundant lapilli of graphitic schist. It is concluded that the lapilli were incorporated into the parental pyroclastic flow as it passed over the basement of metasedimentary rocks.

Table 3. Chemical analyses of tuffs from the Ocaña Formation

Sample	**PND-356**	**PND-359**
SiO_2	62.28	63.83
TiO_2	0.78	0.60
Al_2O_3	16.2	15.58
Fe_2O_3	5.12	5.49
MnO	0.09	0.09
MgO	1.77	2.60
CaO	4.9	5.33
Na_2O	3.77	2.58
K_2O	1.67	2.50
P_2O_5	0.12	0.10
LOI	2.47	1.16
TOTAL	**99.17**	**99.85**

At the eastern end of the Ocaña section the tuffs of the Ocaña Formation are overlain by sediments of the Puñay Unit. Rare bedding surfaces and eutaxitic textures indicate the Ocaña tuffs are folded. It is therefore difficult to calculate the thickness of the tuffs, but they are estimated to have an approximate thickness of between 400 and 500 m.

Egüez et al. (1988) previously identified the rocks of this section as andesitic lavas and assigned them to the Macuchi Formation (*sic*). However, the present work clearly indicates that the sequence is composed of dacitic tuffs, which cannot be part of the Macuchi Unit by virtue of their structural position, resting upon metamorphic basement to the south-east of the Bulubulu Fault.

4.7.2.3 The Ocaña Formation in the Chanchán Valley-Huigra area: The dacitic ash-flow tuffs of the formation can be traced in a continuous belt from the Ocaña area as far north as the Chanchán Valley, where they are exposed in cliffs along the Huigra-El Triunfo road between the Quebrada San Carlos [7151-07428] and Río Angas [7178-97419]. Here the formation is faulted against the pillow basalts of the Pallatanga Unit to the west. The section consists of a single, massive, crystal-rich welded dacitic ash-flow tuff, virtually identical in appearance to the main tuff unit seen in the Ocaña-Javín section. The tuff contains abundant feldspar and rounded quartz crystals in a dark grey glassy matrix. In thin section the rock is seen to be ultra-welded, having a matrix composed largely of pale brown glass in which the welding fabric is so extreme as to suggest rheomorphism after deposition of the tuff.

The formation is also well-exposed in the prominent escarpment of Filo de Chasmay [7242-97500] situated immediately to the north of Huigra. Here about a 1000 m of dacitic crystal-rich lapilli ash-flow tuffs are exposed, some of which have strong eutaxitic textures. These dip towards the north-west and west. On the west side they are faulted against basalts of the Pallatanga Unit, and to the north-east they pass beneath younger andesitic rocks of the Cisarán Formation.

4.7.2.4 Summary and discussion of the Ocaña Formation: The Ocaña Formation is the oldest dated lithological unit within the Saraguro Group. It consists predominantly of massive, strongly welded dacitic ash-flow tuffs of uppermost Middle Eocene to Late Eocene age, that were deposited on a basement of metasedimentary rocks. It is uncertain whether the formation is older or younger than the Chulo Unit (see next section).

Previously the Saraguro Group had been assigned an Oligocene age, but the new dates obtained from the Ocaña Formation now indicate that the volcanic activity of the Group began much earlier. It is also considered significant that dacitic ash-flow tuffs of the same age (37.8 ± 3.5 Ma) and general composition are intercalated within turbiditic sediments of the Angamarca Group a relatively short distance to the west in the Pallatanga-Cumandá-La Troncal area (see section 4.6.3). These are believed to represent the same early Saraguro Group activity, during which ash-flow tuffs erupted upon the metamorphic basement of the continental margin and flowed westwards into the forearc sedimentary basin of the Angamarca Group.

4.7.3 Chulo Unit (E_{Sc})

The Chulo Unit crops out in the high part of the Cajas area between Chulo [6980-97003], Laguna Totoras [6976-96930] and San Felipe de Molleturo. It is composed of rhyodacitic and rhyolitic tuffs, breccias, tuffaceous sediments, lavas and high-level intrusions.

4.7.3.1 Stratigraphical relationships and age of the Chulo Unit: Due to lack of time and difficult access the Chulo Unit has not been examined in sufficient detail. Its stratigraphy and structure are therefore not fully understood.

The strata of the Chulo Unit dip mainly to the west and north-west. The base of the unit has not been seen and its relationship with the Ocaña Formation is unknown. The unit is overlain to the north-west by the Filo Cajas Unit. The nature of the contact is not clearly understood, but could be broadly conformable or slightly discordant. The unit is unconformably overlain to the west by the Río Blanco Formation, and to the north, east and south by the Tomebamba Unit, Chanlud Formation and Soldados Formation. It is intruded throughout by andesite dykes related to the overlying Chanlud Formation. These lithostratigraphic units rest with angular unconformity upon the Chulo Unit. This can be seen for example in the Quebrada de Nipalay [6835-96900] between Miguir and San Felipe de Molleturo, where rhyolitic tuffs of the Chulo Unit are folded in a north-easterly trending anticline and overlain subhorizontally by the Río Blanco Formation.

The precise age of the Chulo Unit is not known. It is assumed to be of Late Eocene age, because it is overlain with angular unconformity by tuffs of the Tomebamba Unit which have yielded a basal Oligocene zircon fission-track date. However, as discussed in Section 4.7.2.1 it could conceivably predate the Ocaña Formation and therefore be the oldest unit in the Saraguro Group, and possibly of Middle Eocene age.

4.7.3.2 The Chulo Unit in the Chulo-Baute area: Massive acid lapilli tuffs, tuff-breccias and breccias outcrop in the area immediately surrounding Chulo [6977-97003], as for example in the valleys of the Río Chochuayacu and Río de Curiquinga to the west, and in the ridge of Cerro Padre Rumi to the east [6975-96980]. These rocks are believed to represent the oldest exposed part of the unit. They are white-weathering, recrystallised and somewhat altered, and are intruded by numerous andesite dykes related to the overlying Chanlud Formation. Some of the tuff-breccias have eutaxitic textures and are interpreted as the products of pyroclastic flows, although others are polymictic lithic breccias of probable epiclastic origin.

The breccias and tuff breccias pass up into a stratified sequence of rhyolitic-rhyodacitic ash-flow tuffs. These are exposed to the west of Chulo near Laguna Unsidas [7015-96998] and immediately west of Laguna Sasarín at [7000-97012]. At least four ash-flow units, each between 5 and 15 m thick, are exposed at both of these localities. They are massive and have eutaxitic textures highlighted by fiamme consisting of flattened pumice lapilli. At Laguna Sasarín the topmost tuff is overlain by andesite lavas of the Chanlud Formation.

Similar rocks outcrop to the south-east of Chulo in the region around Baute [6968-96991] where they form a well-featured north-westerly dipping sequence (Plate 1). The oldest exposed rocks are massive, white and pale pink-purple weathering rhyolitic breccias and tuff-breccias which outcrop on the east side of the valley in the ridge of Cerro Padre Rumi. Passing westwards (up the succession) there is no exposure in the valley floor due to a covering of moraine, but the ground is probably underlain by flaggy rhyolitic tuffs and reworked tuffs which outcrop farther south-west in the head of the valley. On the west side of the valley a well-featured, stratified sequence of ash-flow tuffs outcrops. The lowest exposed unit is a massive, strongly welded rhyolitic ash-flow tuff approximately 120 metres thick. This has very well-developed columnar cooling joints and forms the prominent hill at [6954-96970]. At the southern end of the hill this tuff can be seen resting on deeply weathered flaggy rhyolitic tuffs and reworked tuffs which cover a large area of the higher ground to the south-west extending as far as the main road (see section 4.7.2.3). The columnar jointed tuff is overlain by a series of four or five thinner rhyolitic and rhyodacitic ash-flow tuffs each 10-15 metres thick. These thinner tuff units are exposed to the north-east of Laguna de La Casa [6950-96985] and appear to dip beneath the Filo Cajas Unit which forms the prominent escarpment on the north-west side of the lake.

4.7.3.3 The Chulo Unit between Laguna Totoras and the summit of the Cajas road: The rocks of the Chulo Unit are well-exposed adjacent to the main road running through the highest part of Cajas, in the area around Laguna Totoras [6976-96930] and farther to the west.

Acid breccias, tuffs and rhyolites outcrop around Laguna Totoras and in the ground immediately to the west. The rhyolites are flow-banded, flow-folded and flow-brecciated and show both intrusive and extrusive contact relationships. Excellent exposures of flow-banded and autobrecciated rhyolites are exposed in road cuttings at [6962-96929]. The two prominent hills on the northern and western side of Laguna Totoras are rhyolite domes which are thought to be high-level intrusive bodies. Another dome occurs at [6958-96940] and is well-exposed adjacent to the path that leads northwards towards Patul. Here complex relationships can be seen between flow-banded, flow-folded and autobrecciated rhyolites. Not all the breccias in this area are autobreccias. Some are matrix-supported debris-flow breccias containing polymictic lithic clasts, a high proportion of which consist of coarse, angular blocks of flow-banded rhyolite. This is taken as evidence that the rhyolite domes of this area must have been partly extrusive, and that their breccia carapaces were reworked by mass-flow processes.

Pale green rhyodacitic tuffs overlie the breccias in the cliffs on the west side of Lagunas Ataucocha [6963-96952]. These are welded and have pronounced eutaxitic textures and contain rounded quartz crystals and abundant dacitic lithic lapilli. An excellent section occurs through an almost identical tuff along the main road immediately to the east of the summit (4134 m) [6958-96933]. This exposes a massive, pale green, rhyodacitic tuff at least 50 metres thick, which has a pronounced eutaxitic texture and is strongly welded. It contains abundant dacitic or rhyodacitic lithic lapilli and blocks which are coarsest and most abundant towards the base of the flow unit (at the eastern end of the exposure) where they account for at least 40% of the rock. The matrix exhibits good vitroclastic textures and contains abundant feldspar and rounded quartz crystals.

4.7.3.4 Tuffs and volcaniclastic rocks of the Cerro Arquitecto-Pampladas area: A distinctive sequence of well-stratified rhyolitic tuffs and tuffaceous sediments outcrops in a syncline immediately to the west of the summit of the main road. These are exposed in road cuttings downhill from the prominent bend in the road at [6951-96934], although a more complete section can be seen to the south of the road in the cliffs of Cerro Arquitecto [6943-96928] where approximately 100 m of bedded sediments are exposed. The section consists of well-bedded, white tuffaceous sediments, which include turbiditic volcanic arenites, siltstones, laminated dust tuffs, pumiceous debris-flow microbreccias and thin rhyolitic ash-flow tuffs. This well-bedded sequence is believed to have been deposited in a lacustrine environment and is overlain in the summit area of Cerro Arquitecto by a highly siliceous rhyolitic ash-flow tuff more than 100 m thick. This uppermost tuff has prominent columnar cooling joints and a very strongly developed eutaxitic texture. In thin section it is seen to be ultra-welded.

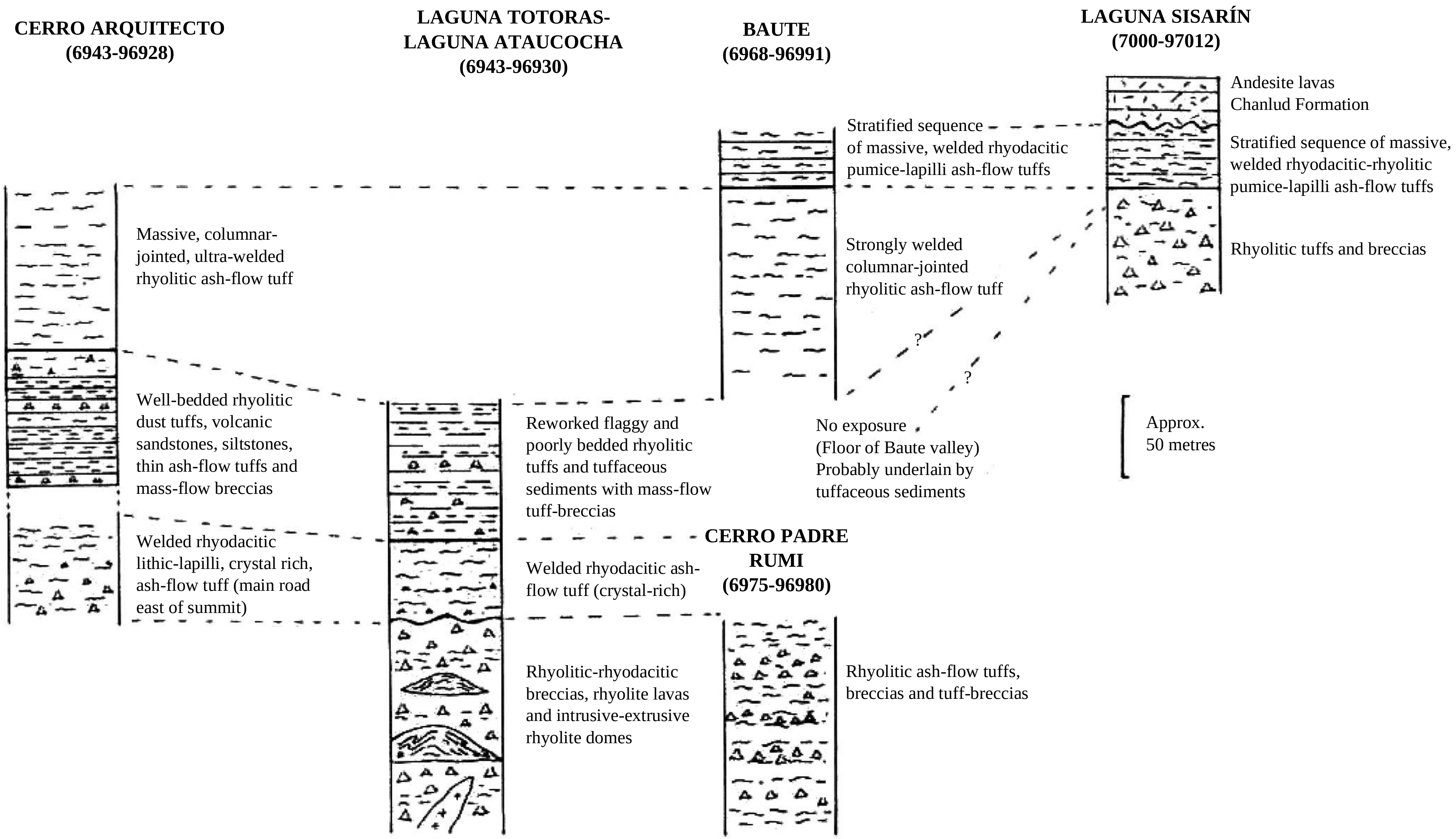


Figure 17. Generalised correlation within the Chulo Unit

To the north of the road the well-bedded volcanic sediments pass into an area of complex and chaotically mixed tuffs and sediments. In the corrie on the east side of Pampladas [6934-96944] several hundred metres of massive, white-weathering rhyolitic tuff are exposed in a cliff face (Plate 2). Abundant clasts of sediment are supported within the tuff and show deformational evidence of having been wet and plastic at the time of incorporation. These include clasts of siltstone, mudstone, sandstone and breccia of green and red-brown colour, ranging in size from less than a centimetre up to several tens of metres. Small carbon fragments also occur throughout. The white tuff matrix supporting the clasts is deeply weathered and has a sandstone-like texture, but in thin section is seen to be composed almost entirely of very fine, undeformed (unwelded) delicate cuspate shards (now recrystallized). The tuff is overlain at the top of the cliff by dark grey tuffaceous siltstones and sandstones which together with the tuff show evidence of large-scale slumping and soft sediment deformation which has produced a mélange with large-scale flames and sedimentary dykes extending downwards into the tuff for depths of up to 100 metres. Near the top of the cliff a large raft of tuff more than 50 m across appears to be enveloped in sediment.

At the scale of mapping little could be done to unravel the complexities of this location. Nevertheless, it appears that several events took place to produce these mixed rocks. Firstly, a large rhyolitic ash-flow appears to have been erupted into a sedimentary basin, incorporating clasts of wet sediment into the body of the tuff. The very fine vitroclastic texture of this tuff could be taken as evidence for an extremely explosive event caused by interaction of the pyroclastic flow with water when it entered the lacustrine environment. Following further deposition of (dark grey) sediment on top of the tuff, instability caused more slumping and mixing of sediment and tuff resulting in the formation of large-scale flame structures and sedimentary dykes.

The massive white tuffs containing sediment clasts can be traced north-eastwards into the high ground around Cerro Amarillo [6937-96958] and farther eastwards [6955-96955]. They include secondary tuffs which show evidence of reworking and slumping. In the highest ground they are crudely stratified and dip northwards beneath the thick, columnar jointed and welded ash-flow tuff which forms the prominent hill south of the Baute area (section 4.7.3.2).

An instructive exposure also occurs on the high ground a short distance to the north of the main road at [6952-96947]. Here debris-flow breccias show features consistent with having been hot and wet at the time of emplacement. They contain lithic clasts which are held loosely in larger cavities within a clay-rich matrix. Such cavity-surrounded clasts are a feature of phreatomagmatic deposits formed by the generation and expansion of steam around hot clasts incorporated within a wet matrix.

4.7.3.5 Summary and discussion of the Chulo Unit: The Chulo Unit consists of rhyolitic and rhyodacitic tuffs, breccias, volcaniclastic sediments and intrusive-extrusive rhyolites. The unit is considered to be of Late Eocene age, but it could be older.

Although more detailed work is necessary to elucidate the stratigraphy of the Chulo Unit, a number of distinctive rock units allow broad correlations to be made between the three areas described in the previous sections, as illustrated in Figure 17.

Breccias, tuff-breccias and tuffs exposed in the eastern part of the unit's outcrop between Laguna Totoras and Chulo are thought to be the oldest exposed part of the unit. Flows and intrusive-extrusive domes of rhyolite are present within the breccias. The breccias include autoclastic and epiclastic breccias which developed around the domes.

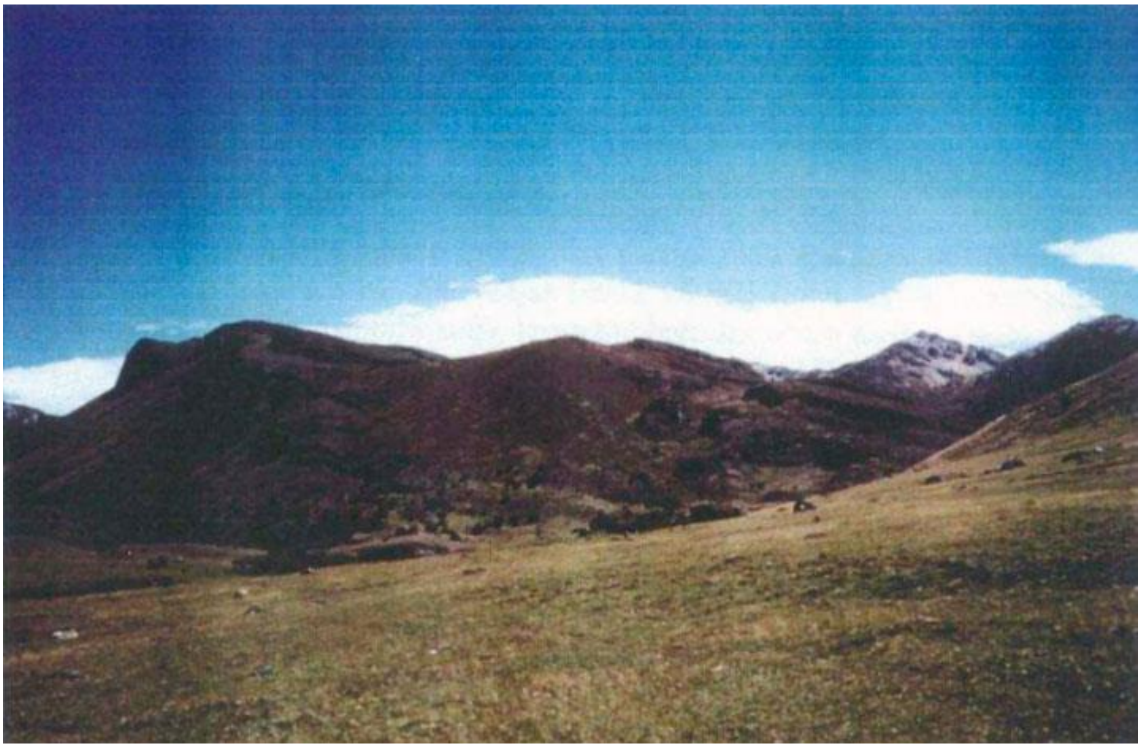


Plate 1. North-westerly dipping welded rhyolitic tuffs of the Chulo Unit at Baute, viewed from the north. The peak in the distance is the summit of Filo Cajas

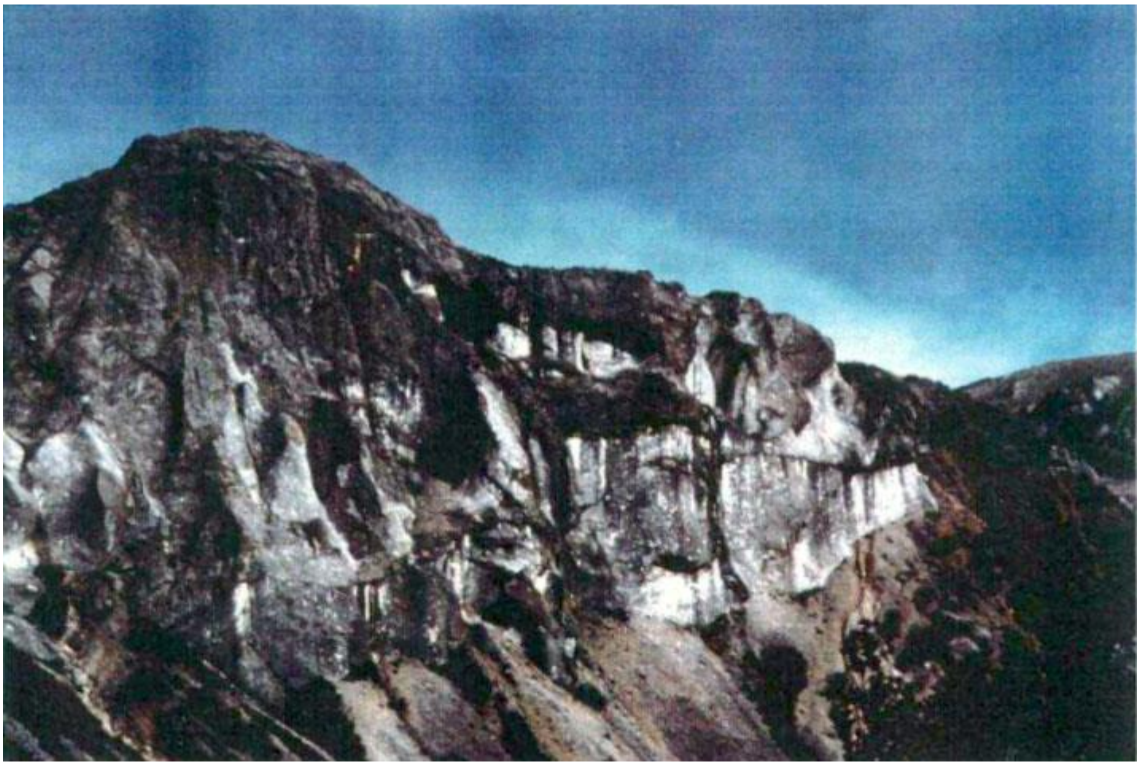


Plate 2. The Chulo Unit in the cliff face near Pampladas [9651-96944]. The cliff is approximately 150 m high and shows chaotic mixing of the pale grey, massive, unwelded rhyolitic ash-flow tuff with the darker sediments. Dykes and flames of darker sediments can be seen intruding the tuff

The breccias are overlain by several rhyodacitic ash-flow tuffs. These are in turn followed by a complex sequence of reworked tuffs and sediments. The sediments are considered to be of lacustrine origin and include rhyolitic dust tuffs, siltstones, mudstones, volcanic sandstones, debris-flow breccias and ash-flow tuffs. In the Cerro Arquitecto area these form a well-stratified and coherent sequence, but elsewhere they appear to have been disturbed by rhyolitic pyroclastic-flows which entered the lacustrine environment causing large-scale slumping and mixing, and the intrusion of sedimentary dykes and flames, as can be seen around Pampladas.

The complex sequence of mixed sediments and reworked tuffs is overlain by a number of welded rhyolitic ash-flow tuffs. The lowest of these is exposed in the Baute and Cerro Arquitecto areas and is highly siliceous, intensely welded and columnar jointed and reaches thicknesses of up to 120m. This is overlain by several thinner ash-flow tuff units in the Baute-Chulo area.

4.7.4 Filo Cajas Unit (E?-O?$_{Sfc}$)

The Filo Cajas Unit outcrops in the highest part of the Cajas area and derives its name from the escarpment of Filo Cajas [6932-96967] (Plate 3). It is composed predominantly of dacitic ash-flow tuffs, lavas and breccias which form a gently north-westerly dipping sequence. Rhyodacitic and rhyolitic tuffs and lavas also occur in the upper part of the unit.

4.7.4.1 Stratigraphical relationships and age of the Filo Cajas Unit: The age of the Filo Cajas Unit is uncertain. It overlies the Chulo Unit, probably unconformably but without angular discordance, and it is overlain by lavas of the Chanlud Formation. It is also intruded by dykes which acted as feeders to the Chanlud Formation. It therefore has a minimum age equivalent to the Late Eocene or Early Oligocene. The fact that it overlies the Chulo Unit without obvious discordance, whereas the basal Oligocene Tomebamba Unit overlies the Chulo Unit with strong angular unconformity, suggests that the Filo Cajas Unit was deformed together with the Chulo Unit prior to erosion and deposition of the Tomebamba Unit. The unit is therefore more likely to be of Late Eocene rather than Early Oligocene age. As discussed in Section 4.7.2.1, the unit could be a correlative of the Ocaña Formation, and therefore could even be as old as the latest Middle Eocene.

4.7.4.2 The Filo Cajas Unit in the area of Filo Cajas and Laguna Playas Encantadas: Intermediate lavas outcrop in the foreground to the south-east of the main escarpment of Filo Cajas around Padre Machay [6925-96937] and the lakes of the Pampladas area [6930-96945]. They have an estimated thickness of 150-200 m and consist of dark to pale grey-green rocks with abundant microphenocrysts of plagioclase. Most flows are dacitic, although some could be of high silica andesite composition. They are uniformly flow-banded and exhibit flow-folding and autobrecciation.

The lavas in the foreground of the escarpment are overlain by a massive dacitic ash-flow tuff approximately 40 metres thick which forms a small NE-trending escarpment or bench-like terrace immediately to the west of the unnamed lake at [6924-96946]. This tuff is mid-green in colour and has a eutaxitic texture highlighted by prominent fiamme consisting of flattened and chloritised pumice lapilli. It contains abundant subrounded to subangular clasts of dacite lava which are very poorly sorted and range up to more than 5 m in size. The very coarse nature of the clasts and their subrounded form are features consistent with the breccias being proximal co-ignimbrite lag breccias, suggesting proximity to the eruptive source.

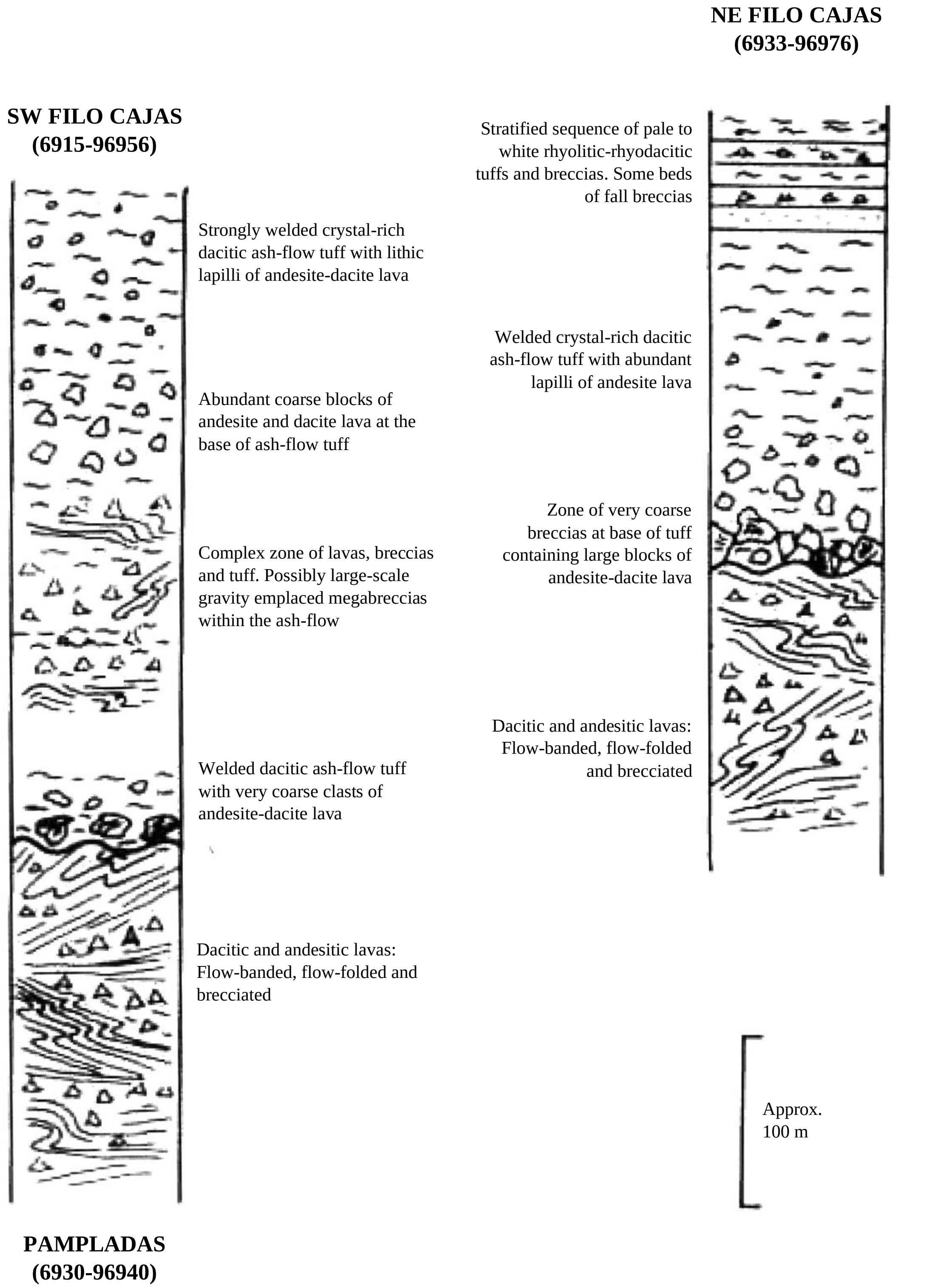


Figure 18. Generalised sections through the Filo Cajas Unit in the Filo Cajas escarpment

Plate 3. Filo Cajas with Laguna de la Casa in the foreground. Looking south-west. The escarpment consists mainly of a dacitic ash-flow tuff of the Filo Cajas Unit overlain at the top of the escarpment by stratified rhyolitic tuffs and breccias

Plate 4. Filo Cajas viewed from the Lagunas Playas Encantadas looking east. The escarpment is composed of a single, welded, dacitic ash-flow tuff

The tuff is overlain by more lavas and breccias, which outcrop around the unnamed lakes at [6917-96944] and form a stratum that can be traced north-eastwards along the base of the escarpment towards Laguna de La Casa. These higher lavas are of dacitic and andesitic composition and are strongly feldspar-phyric. They differ from the lavas at the base of the section (beneath the ash-flow tuff) by being generally more andesitic, richer in feldspar microphenocrysts and considerably more weathered.

A massive columnar-jointed dacitic ash-flow tuff overlies the lavas and forms the main part of the escarpment of Filo Cajas. It appears to be a single tuff unit at least 120 m thick, which dips at about 15 degrees towards the north-west where it occupies all the ground in the vicinity of the Lagunas Playas Encantadas [6910-96945] and the surrounding peaks and ridges (Plate 4). The tuff is dark grey-green in colour and crystal-rich, with abundant feldspar and rounded quartz crystals. It has a marked eutaxitic texture and is strongly welded. Lithic blocks and lapilli of andesite and dacite lava occur throughout the outcrop of the tuff, but are most abundant and coarsest near the base of the unit where they account for up to 50% of the rock and reach more than a metre in size (Plates 5 and 6). These are interpreted as proximal co-ignimbrite lag breccias.

4.7.4.3 The Filo Cajas Unit between Filo Cajas and Quinuas: The large dacitic crystal-rich ash-flow tuff which makes up the main part of the escarpment of Filo Cajas is overlain by a well-stratified sequence of white-weathering, acid tuffs and tuff breccias. These dip uniformly to the north-west and occupy the expanse of ground towards Huahualcay [6905-96993] and Quinuas [6980-96990].

The precise nature of these stratified rocks is uncertain because they are deeply weathered and were therefore not examined in thin section. They consist of a thick sequence of relatively thin massive ash-flow tuff units (each 5-10 m), which on the basis of their pale colour appear to be mainly rhyodacitic or rhyolitic in composition. The pale colour of these rocks may however result from weathering because grey dacitic tuffs were observed at several less weathered outcrops. Coarse breccias occur at the base of some tuff units, and are interpreted as lag deposits. Near the summit of the ridge at [6980-96990] a uniformly planar and laterally extensive bed of breccia several metres thick is conformably interbedded with the tuffs. This is composed entirely of coarse lithic clasts and is interpreted as a proximal fall deposit.

Visual examination from a distance with the aid of binoculars from the summit of Filo Cajas indicates that the strata in the ground to the north of the unnamed lakes around [6920-96980] are disrupted by large-scale disharmonic folds, including recumbent structures up to several hundred metres in amplitude. These are interpreted as large-scale slump structures.

4.7.4.4 The Filo Cajas Unit in the Huahualcay-Quinuas area: The stratified sequence of white-weathered acid tuffs described in the previous section is overlain by flow-banded and brecciated dacitic lavas. These are exposed around [6940-97000] and form a major outcrop in the unnamed mountain at [6928-96992]. Farther west dacitic and rhyodacitic ash-flow tuffs and breccias outcrop around the small lake at [6915-96998] and form a large part of the eastern flank of the mountain of Quinuas [6907-96999]. At the top of the mountain, they are overlain by andesitic breccias, lavas and sediments of the Chanlud Formation.

Plates 5 and 6. Breccias in the lower part of the main dacitic ash-flow tuff of Filo Cajas. The clasts consist of flow-banded dacitic lava supported within in a matrix of crystal rich welded tuff. The large clast is more than 3 metres in size

A large intrusion of fine-grained, flow-banded diorite or dacite forms the mountain at [6910-96990]. In appearance it is difficult to distinguish from the lavas into which it intrudes, and is therefore believed to represent a high-level intrusion that was coeval with the Filo Cajas activity.

The area to the north-west of Quinuas is portrayed on the published geological map as Filo Cajas Unit. This ground was not visited during the survey and the map is based only upon the interpretation of aerial photographs.

4.7.4.5 Summary and discussion of the Filo Cajas Unit: The Filo Cajas Unit outcrops in the highest part of the Cajas area. It consists predominantly of dacitic ash-flow tuffs and lavas, but also includes significant volumes of rhyodacitic-rhyolitic tuffs and lavas as well as minor amounts of andesite.

Although the unit has not been studied in sufficient detail, four broad lithological sequences have been recognised. The oldest recognised rocks are dacitic lavas and breccias which outcrop in the south-east. These are overlain by a single massive dacitic crystal-rich ash-flow tuff more than 120 metres thick which forms the main part of the escarpment of Filo Cajas. This major ash-flow tuff unit is overlain with apparent conformity by a well-stratified sequence of thinner ash-flow tuffs and breccias of dacitic to rhyolitic composition. These are in turn overlain by dacitic and rhyodacitic lavas which outcrop in the Quinuas area.

The tuffs contain zones of very coarse, poorly sorted lithic breccias which are interpreted as co-ignimbrite lag deposits. Uniform beds of coarse breccia of air-fall origin also occur. The volume of the tuffs, particularly the massive ash-flow unit making up the main escarpment of Filo Cajas, and the presence of coarse co-ignimbrite lag breccias suggest an eruptive source in the vicinity. The large-scale disharmonic folds and slump structures in the area between Filo Cajas and Quinuas indicate instability at the time of deposition or shortly after. These features taken together suggest the presence of a zone of eruption, subsidence and accumulation of (intracaldera?) tuffs within the Filo Cajas-Quinuas area.

The main dacitic ash-flow tuff exposed in the escarpment of Filo Cajas and the area of Lagunas Playas Encantadas is similar in composition, appearance and mineralogy to the ash-flow tuff of the Ocaña Formation, except that it shows evidence of being more proximal to an eruptive source. Further mapping would be necessary to elucidate the field relationships between the Filo Cajas Unit and the Ocaña Formation, but on the basis of existing evidence there is no reason why the two units should not be correlatives, the former being a proximal equivalent of the latter.

The minimum age of the Filo Cajas Unit is basal Oligocene, this being the age of the lowest tuffs of the unconformably overlying Tomebamba Unit. However, if the correlation with the Ocaña Formation is valid, then the unit could be of Late or possibly even uppermost Middle Eocene age.

4.7.5 Tomebamba Unit (O_{Stb})

A sequence of intermediate ash-flow tuffs crops out in the southern and eastern parts of the Cajas region, and also on the south side of the Cañar valley around San Francisco de Gualleturo [7080-97210]. In the Cajas area the tuffs are best exposed in the Tomebamba valley, from where the unit derives its name.

4.7.5.1 Stratigraphical relationships and age of the Tomebamba Unit: The Tomebamba Unit rests with angular discordance upon rhyolitic rocks of the Chulo Unit. The strata of the Chulo Unit dip to the north-west, whereas the overlying Tomebamba tuffs are subhorizontal or dip gently towards the south-east.

The Tomebamba Unit is overlain by andesitic lavas and breccias and intruded by feeder dykes of the Chanlud Formation. The nature of the contact between the two lithostratigraphic units is very variable. In some areas it appears to be transitional and broadly conformable, whilst in others it is represented by an angular discordance.

A zircon fission-track date of 34.1 ± 1.3 Ma was obtained from an ash-flow tuff (PND-272) sampled from a small roadside quarry at [6999-96918] in the Cajas area. This tuff is considered to be one of the oldest exposed within unit, and the date obtained corresponds to the lowermost part of the Early Oligocene.

4.7.5.2 Nature of the tuffs of the Tomebamba Unit: The Tomebamba tuffs are massive, lithic-lapilli ash-flow tuffs of intermediate composition. They are mid to dark grey-green in colour, with a dark brown weathering patina which commonly has a mauve hue. They contain crystals of plagioclase and of amphibole which are usually chloritised. Quartz crystals are absent or rare, which contrasts with all the other pyroclastic units of the Saraguro Group of the region. In most areas the tuffs show varying degrees of propylitic alteration, containing secondary mineral assemblages of chlorite, epidote, actinolite, calcite and traces of pyrite.

Vitroclastic textures are visible under the hand lens and in thin section. Many of the tuffs are welded and eutaxitic textures are common throughout, being highlighted by dark green chloritised fiamme consisting of flattened pumice lapilli. Lithic lapilli are ubiquitous and consist of intermediate volcanic lithologies. In places these are concentrated in zones at the base of flow units.

The relatively dark colour of the Tomebamba tuffs and the absence of quartz crystals were taken as field evidence for andesitic compositions. Gamma ray scintillometer readings also suggest andesitic to basic dacite compositions. Only three chemical analyses of the tuffs were obtained during the course of the survey (Table 4). These samples were collected from the Tomebamba valley in the Cajas area. Taken at face value, two of the analyses are equivalent in composition to high silica andesite and the other to a very basic dacite. However, when recalculated on a water free basis all three analyses fall in the field of basic dacite according to the TAS classification. On the basis of this information the Tomebamba tuffs are generally considered to be of transitional high-silica andesitic to basic dacitic composition.

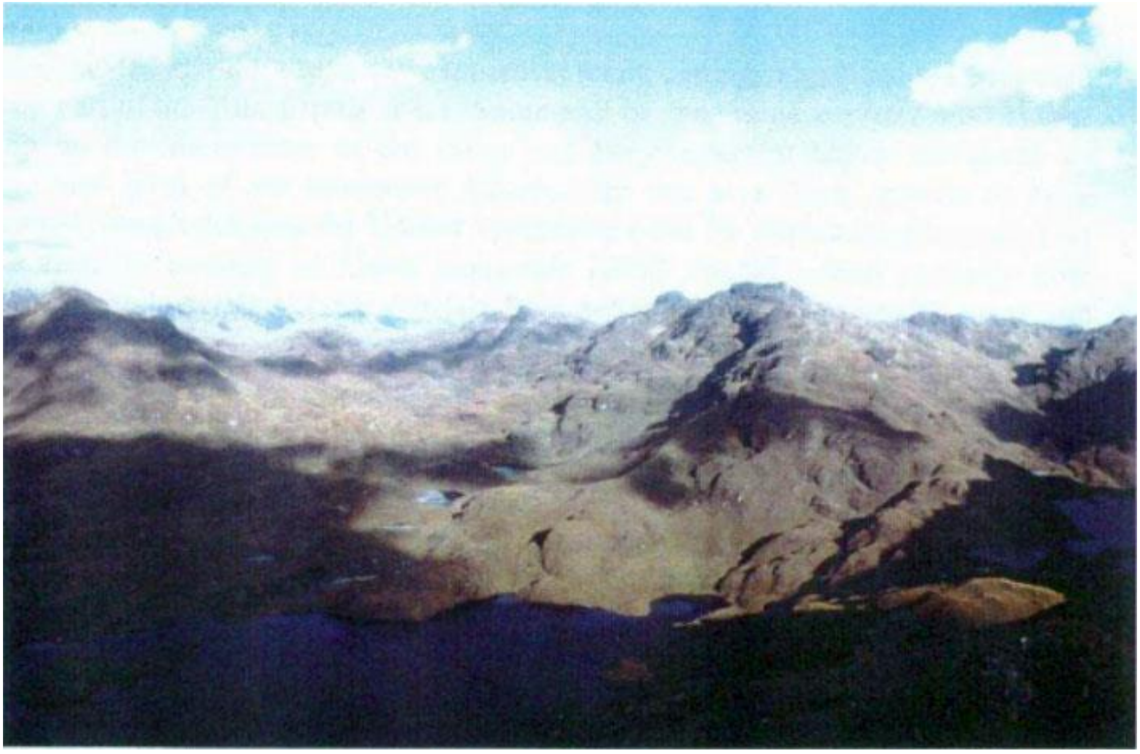


Plate 7. South-western Cajas, looking north-east over Laguna Luspa. The ground in the middle distance consists mainly of intermediate ash-flow tuffs of the Tomebamba Unit

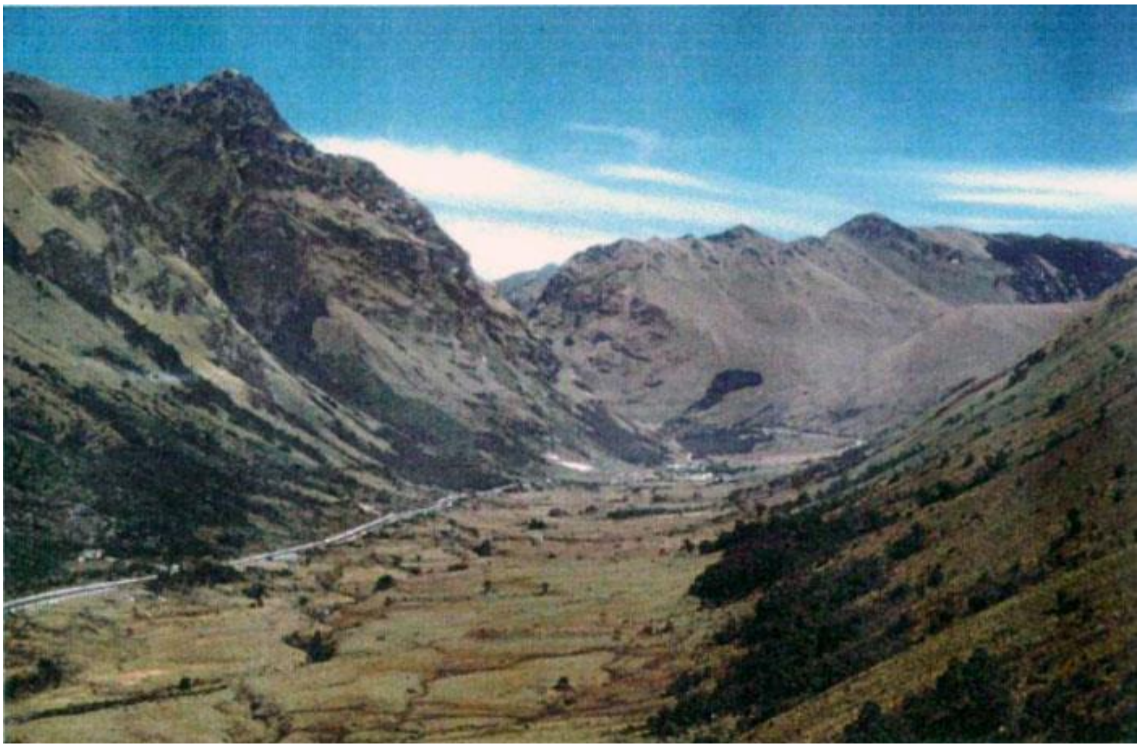


Plate 8. The Tomebamba valley, south-eastern Cajas, looking north-west towards Cerro Guavidula [7032-96921] on the left. The valley sides are composed of intermediate ash-flow tuffs of the Tomebamba Unit, which pass-up through a transitional zone into andesitic lavas and breccias of the Chanlud Formation

Table 4. Chemical analyses of tuffs from the Tomebamba Unit

Sample	PND-272	PND-273	PND-274
SiO_2	61.44	63.56	61.28
TiO_2	0.72	0.64	0.79
Al_2O_3	15.38	15.32	14.96
Fe_2O_3	5.66	4.69	5.73
MnO	0.08	0.07	0.10
MgO	2.87	1.80	2.54
CaO	4.83	4.53	4.24
Na_2O	2.78	2.97	3.31
K_2O	2.15	2.26	2.24
P_2O_5	0.11	0.09	0.13
LOI	3.67	3.10	4.09
TOTAL	**99.69**	**99.03**	**99.41**

4.7.5.3 The Tomebamba Unit in south-eastern Cajas: The unit is best displayed adjacent to the main road through the Cajas recreational area. Here it consists of a series of massive tuffs which are subhorizontally stratified or dip gently towards the south-east.

The tuffs are well exposed to the north of the road around Taquiurcu [7005-96925] where there are several massive, welded, andesitic flow units. Each unit is approximately ten metres thick with basal zones rich in lithic lapilli and blocks. To the west, around Laguna Taquiurcu [7005-96932] and Laguna Billete [7000-96933] these tuffs rest upon rhyolitic and dacitic breccias and lavas of the Chulo Unit, and to the east and north they are overlain by andesite breccias of the Chanlud Formation.

The same ash-flow tuff units are exposed in road cuttings between Taquiurcu and Laguna Apicocha [6990-96921]. At the time of the survey a temporary roadside cutting exposed a massive tuff with carbon fragments including a portion of a carbonised tree trunk. These are considered to be amongst the oldest exposed tuffs of the unit and have yielded a zircon fission track age of 34.1 ± 1.3 Ma from a sample collected from a small roadside quarry at [6999-96918].

Massive, welded ash-flow tuffs are exposed in many cuttings along the road through the main part of the Tomebamba valley. South-east of the bridge at [7042-96922] they outcrop on the lower sides of the valley and are overlain at higher elevations by breccias and lavas of the Chanlud Formation. In this area there appears to be a transitional contact between the Tomebamba Unit and the Chanlud Formation. This can be seen for example on Cerro Guavidula [7032-96921], where andesitic tuffs exposed in the lower flanks are overlain by a series of intercalated tuffs, lavas and breccias.

A similar transitional contact between the Tomebamba Unit and Chanlud Formation can also be seen on both sides of the valley farther to the southeast. An instructive section was examined in the escarpment on the south side of the valley, extending up the Quebrada Verdecocha to the summit of Tres Picos [7046-96882] and then down the south-west side of the ridge to Laguna Taitachugo [7023-96875]. Here gently dipping intermediate ash-flow tuffs of the Tomebamba Unit outcrop in the lower part of the escarpment. These pass up into an alternating sequence of andesitic breccias, scoriaceous andesitic lapilli tuffs and andesitic ash-flow tuffs with a few intercalated lavas and sporadic andesite dykes. The tuffs and breccias within this transitional zone contain strongly vesicular lapilli and scoriaceous blocks of andesite lava which are flattened and agglutinated. Prismatically jointed andesite lava clasts are also present in the tuffs and breccias near the top of the escarpment, and provide evidence that they were probably hot when deposited. These scoriaceous blocky tuffs and breccias are interpreted as the products of scoria-flows and block-and-ash flows (nuées ardentes *sensu stricto*) which were probably erupted from fairly local sources. At the top of the escarpment this transitional sequence passes up into a thick pile of andesite lavas and breccias (of the Chanlud Formation) which dips gently southwards towards Laguna Taitachugo.

4.7.5.4 The Tomebamba Unit in the Río Taitachugo valley: Andesitic and dacitic tuffs of the Tomebamba Unit crop out low on the sides of the valley of the Río Taitachugo to the west of the Laguna Llaviucu [7063-96858]. Passing westwards towards Laguna Taitachugo these are overlain by breccias of the Chanlud Formation.

Several hundred metres of subhorizontal massive andesitic ash-flow tuffs of the Tomebamba Unit crop out in the lower half of the escarpment of Filo Tushipungu on the south side of Laguna Llaviucu. These are overlain with angular discordance by more than 200 m of well-stratified, gently southward dipping, andesitic lavas of the Chanlud Formation. The unconformity can be seen clearly from a vantage point at the junction on the main road at [7087-96862].

4.7.5.5 The Tomebamba Unit around Laguna Labrado: Andesitic lapilli tuffs of the Tomebamba Unit outcrop along the lower sides of the Machángara valley between the represa Chanlud [7185-97042] and Chiquintad. They are overlain at higher elevations on the interfluves by lavas of the Chanlud Formation.

An inlier of the Tomebamba Unit occurs in the Lluquihuaycu valley at the western end of the Laguna Labrado around [7107-96987]. Here a sequence approximately 100 m thick is exposed, consisting of massive, welded andesitic and dacitic ash-flow tuffs intercalated with reworked tuffs, volcanic sandstones and waterlain microbreccias. These are gently folded and overlain with slight discordance by massive lavas of the Chanlud Formation which extend up to the summit of Cerro Lluquihuaycu.

4.7.5.6 Summary and discussion of the Tomebamba Unit: The Tomebamba Unit is of Early Oligocene age and consists essentially of massive ash-flow lapilli tuffs of andesitic to basic dacitic composition. Breccias and tuff breccias also occur locally, particularly near the top of the unit. These include the deposits of block-and-ash flows (nuées ardentes) and scoria flows of probable local origin. Reworked volcaniclastic sediments also occur near the top of the unit.

The tuffs of the Tomebamba Unit rest unconformably upon the Chulo Unit and Ocaña Formation, and are themselves overlain by the Chanlud Formation. In some areas the top of the unit is defined by an angular unconformity surface on which the Chanlud lavas were extruded. Elsewhere, there is a transitional zone between the Tomebamba Unit and Chanlud Formation, in which tuffs, pyroclastic breccias and lavas are intercalated.

4.7.6 Chanlud Formation (O_{Scd})

Intermediate lavas and breccias crop out over an extensive area of the high ground north and west of Cuenca, extending as far as Gualleturo and Suscal in the north and Quinuas [6908-96999] in the west. These rocks are here defined as the Chanlud Formation, being named after the area surrounding the presa Chanlud [7145-96985], situated to the north of Chiquintad.

The formation consists mainly of subhorizontal to gently dipping massive lavas and breccias of intermediate composition, with very minor intercalations of volcanic sandstone, conglomerate and tuff. In general, the lavas are volumetrically much more important than breccias, although in some areas breccias predominate, particularly near the base of the formation. The breccias include both autoclastic and epiclastic types. Andesite dykes are common throughout the crop of the formation and acted as feeders to the lavas.

4.7.6.1 Stratigraphical relationships and age of the Chanlud Formation: The Chanlud Formation rests unconformably upon the Ocaña Formation, the Chulo Unit and the Filo Cajas Unit. It also rests upon andesitic tuffs of the Tomebamba Unit. In some areas the contact with the Tomebamba Unit is broadly conformable and transitional, whilst in others it is represented by an angular unconformity.

The lavas of the Chanlud Formation are unconformably overlain by dacitic ash-flow tuffs of the Soldados Formation in the south, and rhyolitic ash-flow tuffs of the Cerro Caucay Formation in the north.

The relative ages of the Chanlud Formation and Río Blanco Formation are unknown, because contacts have nowhere been recognised between the two formations. Both are andesitic and show the same contact relationships with the underlying and overlying stratigraphical units. On the basis of this evidence, they are believed to be of similar age and probably represent different facies of the same broad phase of andesitic activity.

No radiometric dates have been obtained from the Chanlud Formation. The underlying Tomebamba Unit has yielded a basal Oligocene radiometric date, and the unconformably overlying Soldados Formation and Cerro Caucay Formation have both yielded radiometric dates of uppermost Early Oligocene to earliest Late Oligocene age. By inference, the Chanlud Formation is assigned an Early Oligocene age.

4.7.6.2 Nature of the lavas of the Chanlud Formation: The lavas of the Chanlud Formation have a distinctive appearance and are easily recognised in the field. They mainly occur as thick, massive and laterally extensive flows, which in some respects resemble flood lavas. They are predominantly high-silica andesites, although in some areas dacites and even rare flows of rhyolite occur towards the top of the formation. Representative analyses of lavas from the formation are presented in Table 5.

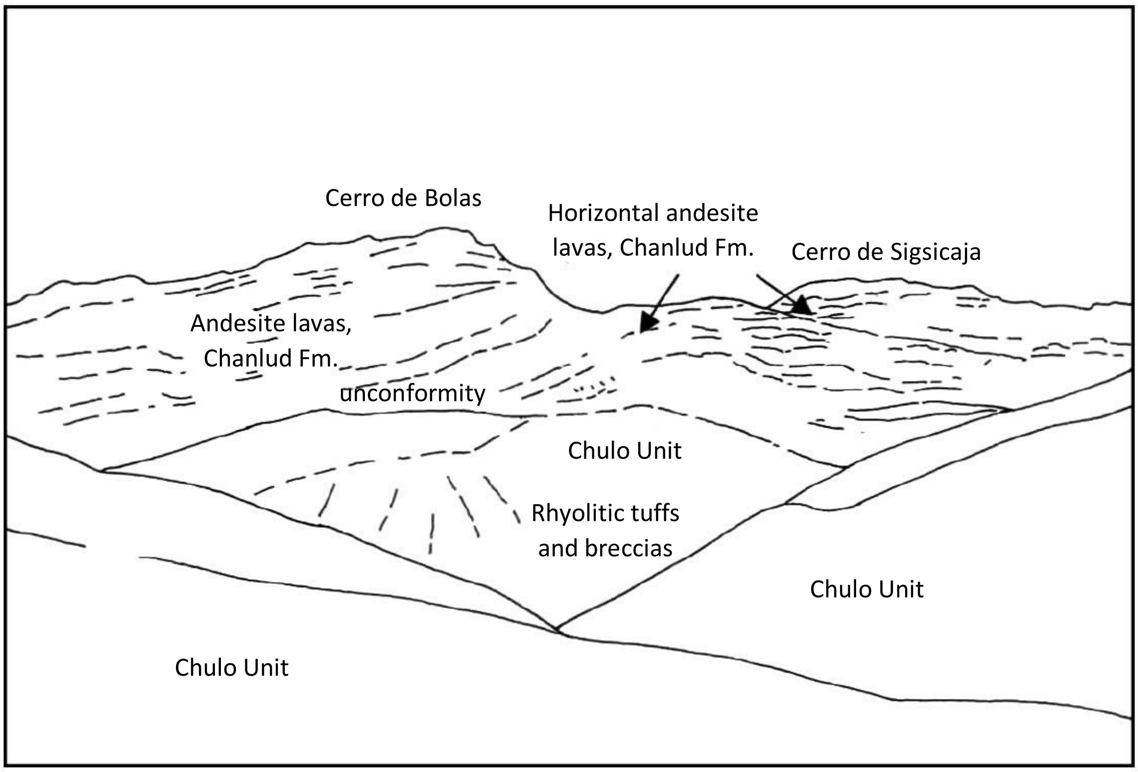


Plate 9. Looking north from near Chulo towards Cerro de Bolas and Cerro de Sigsicaja. The stratified sequence consists of andesitic lavas and subordinate breccias of the Chanlud Formation, which rest unconformably upon acid breccias and tuffs of the Chulo Unit

In unweathered outcrops the andesitic lavas are dark grey or grey-green to almost black. All are strongly feldspar-phyric. Fresh outcrops show a distinctive dark brown to slightly purple-mauve weathering patina, on which fine-scale flow-banding is often apparent. This fine banding is an almost diagnostic feature and provides a useful field criterion for differentiating the lavas from the welded andesitic tuffs of the underlying Tomebamba Unit, which are of similar composition and colour.

In thin section the lavas are seen to contain microphenocrysts of plagioclase, generally between 2-4 mm in size but reaching up to about 7 mm, together with amphibole and clinopyroxene which are invariably altered to chlorite and epidote. Matrices are fine grained and glassy with pilotaxitic textures formed by the flow-alignment of feldspar microlites and laths.

4.7.6.3 The Chanlud** Formation **in the Chanlud area: Subhorizontal to gently dipping andesite lavas and subordinate breccias outcrop around the dams of Chanlud [7185-97042] and Labrado [7145-96985] and cover a very extensive area to the north and west as far as the Cañar valley. They are well-exposed along the roads leading to the two dams.

The base of the formation is exposed at several localities within this general area. A short distance downstream from the presa Chanlud the lavas can be seen resting upon andesitic tuffs of the Tomebamba Unit along the valley sides. The base can also be seen at the western end of the Laguna Labrado around [7107-96987]. At this locality a few tens of metres of reworked tuffs, volcanic sandstones and waterlain microbreccias are intercalated within the uppermost Tomebamba tuffs and are overlain by massive lavas of the Chanlud Formation.

A few kilometres to the north and west of the presa Chanlud the lavas are overlain by a thick sheet of rhyolitic ash-flow tuffs of the Cerro Caucay Formation which form a horizontal capping in the high ground extending northwards towards Cañar.

The thickness of the Chanlud Formation in the area around Chanlud and to the north is approximately 700 m.

4.7.6.4 The Chanlud Formation in the Patul-Central Cajas area: The thickest development of the Chanlud Formation occurs in the central part of Cajas between the settlements of Patul [6974-97012] and Quinuapamba [7036-9704].

At Laguna Sasarín [7002-97012] rhyolitic ash-flow tuffs of the Chulo Unit are overlain with angular discordance by about 1000 m of subhorizontally stratified andesitic lavas and breccias which form the mountains of Cerro de Sigsicaja [6993-9702] and Cerro Escaleras [7026-97008] (Plates 9 and 10).

The lower half of the sequence consists of massive, laterally extensive andesite lavas, many of which show fine-scale flow-banding and less commonly flow-folding on weathered surfaces. The upper half of the sequence consists of a thick, chaotic pile of rubble, autobrecciated and scoriaceous andesite lavas intermixed with coarse, poorly sorted epiclastic breccias of the same composition. Contact relationships between the scoriaceous lavas and breccias are complex, and the upper part of the pile is intruded by many irregular dykes, sheets and pods of andesite. The deep weathering of these poorly consolidated rocks gives rise to the characteristically serrated peaks of Cerro de Sigsicaja and Cerro Escaleras.

Table 5. Chemical analyses of lavas from the Chanlud Formation

Sample	**PND-288**	**PND-1168**	**PND-1192**	**PND-1350**	**PND-1364**	**PND-1370**	**PND-1402**	**PND-1421**	**PND-1659**	**PND-1907**	**PND-2125**
SiO_2	59.95	56.17	60.96	57.70	63.95	53.52	58.65	66.37	59.04	58.18	73.95
TiO_2	1.21	0.83	0.73	0.75	0.65	0.62	0.84	0.62	0.89	0.79	0.25
Al_2O_3	16.56	20.51	16.11	17.81	16.56	16.94	17.18	16.38	17.14	17.35	12.31
Fe_2O_3	8.57	6.67	6.09	6.97	4.64	6.97	7.26	5.02	8.06	7.12	3.26
MnO	0.17	0.09	0.11	0.13	0.14	0.11	0.13	0.11	0.15	0.13	0.08
MgO	2.10	2.92	2.67	3.30	0.63	3.12	3.39	2.01	2.92	3.36	0.89
CaO	5.54	6.52	5.27	6.80	5.98	9.49	7.03	0.49	6.17	5.48	1.22
Na_2O	3.46	2.71	3.37	2.62	3.13	2.42	2.45	4.48	2.87	2.94	2.06
K_2O	1.41	0.97	2.25	1.07	1.68	0.43	1.44	3.32	1.64	2.07	2.61
P_2O_5	0.29	0.22	0.17	0.19	0.22	0.16	0.21	0.15	0.20	0.18	0.05
LOI	1.21	2.44	2.27	2.64	2.05	5.81	1.41	1.51	1.21	1.89	2.77
TOTAL	**100.47**	**100.05**	**100.00**	**99.98**	**99.63**	**99.59**	**99.99**	**100.46**	**100.29**	**99.49**	**99.45**
Ba	595	359	-	448	544	255	571	1955	521	608	763
Ce	49	13	-	10	11	2	53	2	31	21	-
Co	20	17	-	24	10	22	20	17	21	21	-
Cr	8	9	-	18	7	56	35	33	15	37	-
Cs	<1	1	-	2	1	2	1	1	1	<1	-
Hf	<3	<3	-	<3	<3	5	7	4	6	<3	-
La	24	11	-	13	11	7	16	12	12	19	-
Nb	8	5	-	5	7	4	9	8	6	8	27
Nd	23	19	-	10	15	12	26	9	21	18	-
Ni	4	6	-	17	3	28	25	17	6	15	-
Rb	40	20	-	26	33	5	36	102	48	68	108
Sc	22	20	-	25	15	28	23	19	21	15	-
Sm	<3	<3	-	3	<3	4	14	10	9	9	-
Sr	305	384	-	458	338	393	275	189	348	359	134
Ta	<3	<3	-	<3	<3	<3	<3	4	<3	3	-
Th	1	1	-	1	2	2	2	4	1	3	-
U	3	2	-	<2	<2	2	<2	2	2	4	-
V	110	164	-	179	85	190	145	107	196	165	-
Y	41	20	-	18	23	15	30	15	23	21	25
Zr	176	97		105	131	80	170	127	115	185	181

4.7.6.5 The Chanlud Formation adjacent to the Tomebamba Valley: The Chanlud Formation can be seen resting upon the Tomebamba Unit on both sides of the main road along the Tomebamba valley in the southeast of Cajas.

On the north-east side of the valley a thick sequence of coarse, poorly-sorted andesite breccias makes up the basal part of the formation and passes up into andesite lavas and breccias which outcrop on the higher peaks and ridges extending to the north and east towards the Chanlud area. Some of the breccias are autoclastic, but the majority appear to be epiclastic. They are crudely stratified, very coarse and poorly sorted and exhibit clast-supported and matrix-supported fabrics. Clasts consist of strongly feldspar-phyric andesite lava. The matrix-supported breccias weather to a pale green colour and have strongly feldspathic matrices of the same general appearance as the clasts. The strong weathering of these breccias gives rise to a distinctively pillared topography, as can be seen for example on the flanks of Cerro Padreurcu [7008-96943] to the north of the main road.

The escarpment on the south-west side of the Tomebamba Valley exposes a gradational contact between the lavas of the Chanlud Formation and the underlying tuffs of the Tomebamba Unit. This was examined in a section from the valley floor up the Quebrada Verdecocha to the summit of Tres Picos [7046-96882] and then down the south-west side of the ridge to Laguna Taitachugo [7023-96875]. Gently dipping intermediate ash-flow tuffs of the Tomebamba Unit outcrop on the lowest valley sides. These pass up into an alternating sequence of andesitic breccias, scoriaceous andesitic lapilli tuffs and andesitic ash-flow tuffs with a few intercalated lavas and sporadic andesite dykes. The tuffs and breccias within this transitional zone contain strongly vesicular lapilli and scoriaceous blocks of andesite lava which are flattened and agglutinated. Prismatically jointed andesite lava clasts are also present in the tuffs and breccias near the top of the escarpment. These scoriaceous blocky tuffs and breccias are interpreted as the products of scoria-flows and block-and-ash flows (nuées ardentes *sensu stricto*), and were probably erupted from a fairly local source. At the top of the escarpment this transitional sequence passes up into a thick pile of andesite lavas and breccias of the Chanlud Formation which dip gently to the south towards Laguna Taitachugo.

4.7.6.6 The Chanlud Formation along the southern margin of the Cajas area: Lavas of the formation outcrop extensively along the southern margin of the Cajas area. They are predominantly andesitic although the uppermost flows are dacitic or even rhyolitic.

A sequence of more than 200 m of well-stratified, gently southward dipping andesitic lavas of the Chanlud Formation overlie tuffs of the Tomebamba Unit with angular discordance in the escarpment to the south of Laguna Llaviucu [7063-96858]. The unconformity can be seen clearly from the junction on the main road at [7087-96862]. At least eight massive, fine-grained lava flows have been recognised. Most are andesitic but the topmost flow is dacitic in composition and intensely flow-banded from the base to the top. At the top of the escarpment in the Filo Tushipungu, the uppermost lava is capped by acid ash-flow tuffs which are tentatively correlated with the Plancharumi Formation.

Farther west and south-west, massive, laterally extensive lavas of the Chanlud Formation outcrop over a large area within the headwaters of the Río Mazán. In this area the lavas dip gently to the south-east and are overlain unconformably by dacitic crystal tuffs of the Soldados Formation. The contact can be seen in the escarpment along the southern side of the Mazán basin, where the lavas form the main part of the escarpment whilst the overlying tuffs form the peaks of Cerro Cotes [6987-96800], Cerro Tinta Cocha [7002-96802] and Soldados [7032-96801]. The contact has been examined at [6974-96813]. Here the uppermost lava is dacitic or rhyodacitic and is overlain by several metres of dacitic breccias, which are in turn overlain by the crystal tuffs of the Soldados Formation.

Plate 10. Cerro Escaleras [7026-97008] viewed from the east. The peaks are composed of andesitic breccias and lavas of the Chanlud Formation, intruded by andesite dykes and sheets

Plate 11. Cerro Ventanillas [6958-97006] viewed from the east. The escarpment consists of subhorizontal andesite lavas and breccias of the Chanlud Formation, intruded by numerous vertical feeder dykes of andesite

4.7.6.7 Conglomerates and other sediments: Conglomerates and volcanic sandstones occur at a number of localities within the Chanlud Formation.

The basal part of the formation is exposed at Pallcarumi [6990-97180] on the footpath between Cargua and San Antonio de Gualleturo. Here coarse andesitic conglomerates and breccio-conglomerates with beds of red-purple sandstones and siltstones are intercalated with lava flows.

A thick sequence of coarse, poorly stratified andesitic conglomerates and breccio-conglomerates outcrop in the area immediately to the south of Suscal, around the Quebrada Capulí [7164-97274]. The clasts are identical in appearance to the lavas of the Chanlud Formation.

On the east side of Cerro Escaleras at [7030-97006] about 15 m of well-stratified breccio-conglomerates and tuffaceous sandstones and tuffs are exposed.

4.7.6.8 Andesite dykes and sills: An andesite dyke swarm occurs within the formation and intrudes all the older stratigraphic units in the Cajas area. The dykes have the same general appearance and composition as the lavas to which they are assumed to have acted as feeders. The full distribution of these dykes is unknown, due to the relatively wide spacing of the geological traverses undertaken during the survey. However, based on the available information, the greatest concentration of dykes occurs in the highest ground around Filo Cajas and Patul. The dominant trend is NW-SE, although a radial distribution pattern is developed around Patul. Here the dykes also reach their greatest size, being up to 10 m in width and up to a kilometre in length. Several dykes of this size occur at the northern end of Filo Cajas around [6947-96997] and are visible on aerial photographs. The dykes are particularly intensely developed on the eastern flank of Cerro Ventanillas [6958-97006] (Plate 11) where the amount of extension is crudely estimated to be of the order of 15%.

The Chanlud Formation is also intruded by high-level apophyses or discordant sills of the meladiorite or andesite of the same appearance and composition as the lavas. The largest of these intrusions occurs around Laguna Chorreras [7047-96940], and another similar and probably related sill occurs between Cerro Tres Cruces [7045-96985] and Cerro Cajas [7060-96970]. A smaller body intrudes into the formation near Cerro Cipriales [6951-96877]. Andesite dykes cross-cut all three of these intrusions and are intensely developed around the Cerro Tres Cruces-Cerro Cajas intrusion.

4.7.6.9 Summary and discussion of the Chanlud Formation: The Chanlud Formation is of Early Oligocene age and consists predominantly of subaerially erupted andesite lavas and breccias, although dacitic and even rhyolitic lavas occur at the top of the formation in the south and south-west. The products of scoria flows and block-and-ash flows of local origin occur at the base of the formation in the south-east, where there appears to be a transitional contact with the underlying Tomebamba Unit. Minor amounts of volcaniclastic sediment also occur locally.

The formation reaches its thickest development in the Patul-Quimepamba area. Here a thick pile of lavas and coarse, poorly sorted scoriaceous breccias form the mountains of Cerro Escaleras and Cerro Sigsicaja and are injected by a radial swarm of dykes. The thickness of the formation in this area, together with the scoriaceous breccias and the radial dyke swarm suggests an eruptive centre existed in this area.

The lavas are very extensive and voluminous. Taking a conservative average thickness of 500 m, the volume of the formation within the present limits of outcrop would be approximately 600 km^3.

The uniformly thick, massive and extensive forms of individual flows more closely resemble the morphology of flood lavas, rather than the laterally restricted, complex forms typically associated with subaerial intermediate calc-alkaline lavas. The high-silica andesite composition of the lavas may at first appear to be at variance with their laterally extensive form. However, the most influential factor controlling morphology was probably the rate of eruption, rather than magma viscosity, with high rates of eruption producing extensive flows (c.f. Walker, 1973).

The presence of numerous NW-trending feeder dykes within the formation indicates NE-SW tension at the time of eruption. It is believed that such a stress regime could have formed in a pull-apart structural setting in response to strike-slip movement along the major NE-SW trending regional faults (e.g. the Bulubulu and Chimbo-Cañi faults). Such a tensional regime could have facilitated the rapid passage of magma to the surface resulting in high rates of eruption and extensive flows. This may explain the transition from dominantly explosive activity of the Tomebamba Unit to effusive activity of the Chanlud Formation, even though both stratigraphic units have broadly similar compositions.

4.7.7 Río Blanco Formation (O_{Srb})

The Río Blanco Formation is composed predominantly of lavas and volcaniclastic rocks of predominantly andesitic composition, with lesser volumes of dacitic and rhyodacitic material. The volcaniclastic rocks include primary ash-flow tuffs, reworked tuffs, volcanic sandstones and debris-flow breccias.

The formation crops out in a broad ridge of high ground which extends north-westwards from Lomo Arquitecto [6844-96860] to Corona de Oro [6740-97065] and is bounded on the south-west side by the Chaucha batholith and to the north-east by the Molleturo diorite. The strata of the formation strike NW and generally dip towards the NE.

The formation is well-exposed along the main Cuenca-Jesús María road between [6825-96921] and [6709-97014]. Good sections also occur in the mountains surrounding the settlement of Río Blanco [6819-96883], from where the formation derives its name.

4.7.7.1 Stratigraphical relationships and age of the Río Blanco Formation: The Río Blanco Formation unconformably overlies metamorphic schists, sheared basalts of the Pallatanga Unit and folded rhyolitic tuffs of the Chulo Unit. It is overlain along the south-east margin by dacitic ash-flow tuffs of the Soldados Formation.

No reliable radiometric dates have been obtained from the formation. The overlying Soldados Formation has yielded radiometric dates of uppermost Early Oligocene to Late Oligocene age, and the underlying Chulo Unit has a minimum Late Eocene age. By inference, the Río Blanco Formation is therefore considered to be of Early Oligocene age.

The stratigraphic relationship between the Río Blanco Formation and the Chanlud Formation is unknown, because they are nowhere seen in contact. However, both formations unconformably overly the Chulo Unit, and both are unconformably overlain by the Soldados Formation. In addition, both are of similar composition, being predominantly andesitic with increasing proportions of dacitic and rhyodacitic rocks in their upper parts. It is therefore possible that the Río Blanco Formation and Chanlud Formation are broadly equivalent and represent different facies of the same general episode of intermediate volcanic activity.

4.7.7.2 The Río Blanco Formation in the Cuenca-Jesús María road section: The Cuenca-Jesús María road cuts obliquely across the strike of the formation. At the western end of the section around [6709-97014] the Formation rests unconformably upon the highly sheared ocean-floor basalts of the Pallatanga Unit. Here the rocks of the formation show evidence of having been deposited in water and consist of siltstones, sandstones, andesitic tuffs, re-worked hyaloclastites and matrix-supported tuffaceous debris-flow breccias. The sandstones and siltstones at the base of the unit are thin-bedded turbidites. Rare clasts of schists occur within the breccias, indicating that metamorphic basement may have been exposed in the area at the time of deposition. Welded dacitic and rhyodacitic ash-flow tuffs also occur in this lower part of the formation, as can be seen for example in the prominent bend in the road at [6725-97011].

The section along the road to the south-east of this prominent bend is dominated by massive andesites. These are melanocratic and at first sight resemble basalts, but chemical analyses and gamma-ray spectrometric measurements indicate that they are high-silica andesites (Table 6, samples PND-267, 268, 270 and 271). They include fine-grained and coarsely feldspar-phyric andesites, which in thin section are seen to contain microphenocrysts of hypersthene and, or amphibole. These rocks tend to be altered into assemblages of chlorite, actinolite, epidote, pyrite and calcite. In the absence of recognisable contacts, it is difficult to decide whether these massive units are lavas or large sill-like intrusions, although local occurrences of breccias and coarse andesitic conglomerates suggest that at least some are extrusive in origin.

Near San Felipe de Molleturo the formation is more clastic in nature and is composed of tuffs, breccias, tuff-breccias and reworked hyaloclastites, as well as lavas with vague pillow structures. Much of the volcaniclastic material shows evidence of having been redistributed and deposited by mass-flow processes. Several fine-grained andesite dykes and sills can be seen intruding the sequence in the road cutting at [6777-96952]. Petrographically and compositionally these are identical to the lavas of the Río Blanco Formation, with which they are assumed to have been broadly coeval. The dykes trend NW-SE, which is the same trend shown by the dykes of the Chanlud Formation.

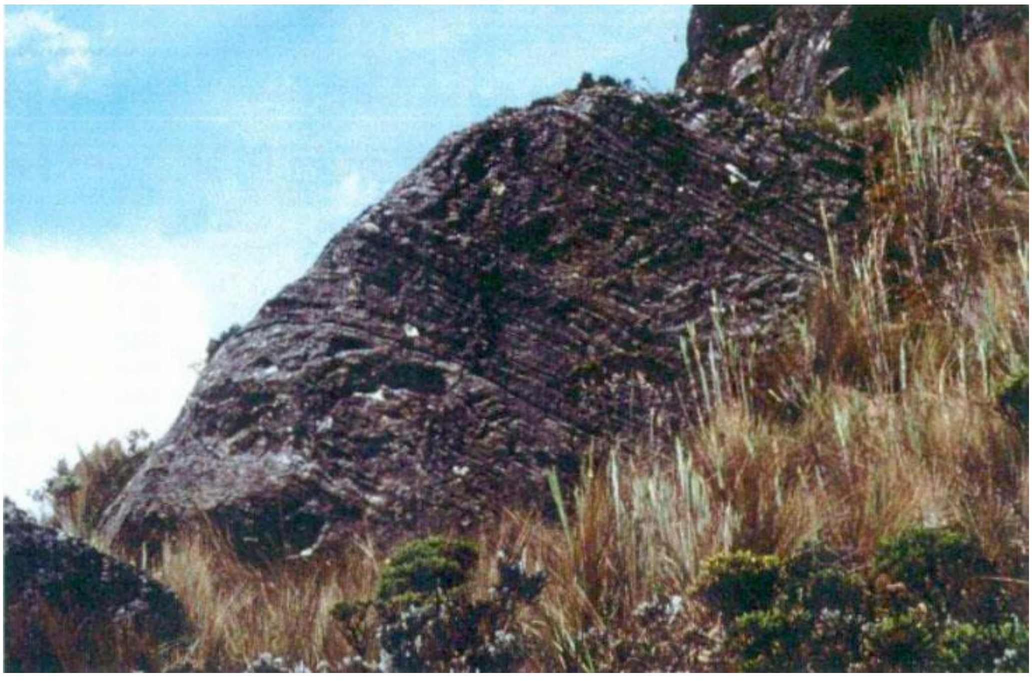


Plate 12. Flow-banded dacitic lavas of the Río Blanco Formation near Laguna Yanacocha de Atugyacu [6872-96878]

Passing eastwards from San Felipe de Molleturo, the rocks exposed along the road section are altered, mineralised and hornfelsed by the Molleturo diorite, the contact of which runs approximately along the line of the road. The original nature of the rocks in many of the road cuttings is difficult to determine because of the hornfelsing, although they appear to be andesitic, and in many outcrops the presence of clasts or lapilli indicate a predominantly volcaniclastic nature. One good exposure can be seen in a roadside quarry immediately to the west of the Río El Chorro at [6811-96913]. This exposes a stratified sequence of pale green, feldspathic, andesitic volcanic sandstones and tuffs. The sandstones are mostly thick-bedded and massive with intercalations of matrix-supported mass-flow conglomerate and breccio-conglomerate. Thin beds of sandstone also occur which are graded and cross-bedded and have small-scale cross-cutting channel structures. The tuffs are massive, rich in feldspar crystals, and exhibit excellent vitroclastic textures manifested by abundant dark green chloritised shards which are sufficiently coarse and well-preserved as to be visible in hand specimens.

4.7.7.3 The Río Blanco Formation in the Río Blanco area: A similar sequence of rocks outcrops in the higher ground around Río Blanco, although here original textures and fabrics are more evident because the rocks are not hornfelsed.

To the north-west of Río Blanco a faulted inlier of biotite schists and gneisses occurs within the formation at the head of Quebrada Llapin [6771-96903]. Although the throw on the bounding faults is unknown it is not considered to be large, and it is therefore assumed that in this area the Río Blanco Formation rests upon metamorphic basement. To the north-east the formation can be seen resting unconformably upon folded acid tuffs of the Chulo Unit in the head of the Quebrada de Niplay [6835-96898].

The rocks are not well-exposed in the area immediately surrounding the settlement of Río Blanco, and some of the outcrops are also strongly silicified as a result of mineralisation. Nevertheless, andesitic ash-flow lapilli tuffs, reworked tuffs, volcanic sandstones and lavas have been recognised. These are intruded by sill-like bodies and sheets of fine-grained meladiorite or andesite which are thought to have been broadly contemporaneous with the volcanism of the formation.

An instructive section can be seen in the southern flanks of Cerro Llapín [6795-96887], which is situated to the north-west of Río Blanco. This consists of a gently dipping sequence of pale green andesitic tuffs, volcanic sandstones and andesitic lavas. The tuffs are feldspathic and contain abundant green chloritic shards. Some of these tuffs are reworked and exhibit graded bedding, small-scale cross-bedding and scour and fill structures. The section is capped by an extensive sequence of subaerial andesite lava flows. These extend westwards from the summit of Cerro Llapín along the ridge towards Cocha Pamba. They are well-displayed along the track which follows the top of the ridge, where they exhibit the most superbly developed flow-banding, flow-folding and flow-brecciation.

Table 6. Chemical analyses of lavas and tuffs from the Río Blanco Formation

Sample	**PND-50**	**PND-267**	**PND-268**	**PND-270**	**PND-271**	**PND-1834**	**PND-1835**	**PND-2165**
SiO_2	60.08	60.67	59.06	59.45	59.03	55.00	62.75	61.46
TiO_2	0.77	0.70	0.68	0.67	0.77	1.03	0.82	0.70
Al_2O_3	15.62	15.87	15.50	15.68	16.00	19.20	17.20	15.38
Fe_2O_3	5.48	7.44	7.56	7.43	7.80	6.89	6.07	4.99
MnO	0.09	0.12	0.16	0.13	0.15	0.13	0.12	0.08
MgO	0.31	3.82	3.64	3.79	3.51	3.62	2.20	2.45
CaO	3.29	6.85	7.13	6.64	7.14	6.94	4.66	6.31
Na_2O	3.05	2.89	2.77	2.99	2.46	2.17	2.63	3.78
K_2O	3.08	1.10	1.00	1.05	0.10	0.99	1.76	0.79
P_2O_5	0.06	0.12	0.11	0.11	0.13	0.37	0.19	0.11
LOI	4.13	0.78	1.93	1.70	2.45	3.29	1.78	3.39
TOTAL	**95.96**	**100.36**	**99.54**	**99.64**	**99.54**	**99.63**	**100.18**	**99.44**
Ba	-	277	280	285	190	357	651	622
Ce	-	23	25	21	25	7	27	-
Co	-	24	25	24	23	17	17	-
Cr	-	42	43	45	31	35	25	-
Cs	-	-	-	-	-	<1	1	-
Hf	-	3	3	<2	3	10	6	-
La	-	9	10	6	11	16	15	-
Nb	-	4	3	3	4	8	6	19
Nd	-	-	-	-	-	13	17	-
Ni	-	17	19	19	13	15	9	-
Rb	-	23	22	22	<1	43	47	43
Sc	-	22	20	24	-	21	15	-
Sm	-	-	-	-	-	3	10	-
Sr	-	230	224	218	232	361	300	387
Ta	-	-	-	-	-	2	<2	-
Th	-	3	1	1	3	1	1	-
U	-	<1	1	<1	2	2	2	-
V	-	152	156	158	162	176	134	-
Y	-	19	18	18	21	20	25	21
Zr	-	103	99	101	109	110	161	138

All the samples are of lavas, except PND-50 which is a tuff.

To the east of Río Blanco good sections are exposed in the mountains of Yantahuaycu [6845-96880] and Lomo Arquitecto [6844-96860]. Here the formation is composed predominantly of interstratified andesitic, dacitic and rhyodacitic tuffs, breccias and lavas with intercalations of volcanic sandstone. The tuffs are massive crystal-rich ash-flow tuffs which are welded and exhibit strong eutaxitic textures. Crystals consist predominantly of feldspar and minor amphibole, although some flow units contain rounded quartz crystals.

Farther south-east, the summit ridge of Filo de los Arquitectos [6856-96855] is composed of lavas and breccias ranging in composition from basaltic andesite to rhyodacite. Thick andesitic and dacitic lavas outcrop on the south-eastern side of this ridge around Laguna Yanacocha de Jérez [6864-96903] and Laguna Yanacocha [6866-96870]. These exhibit well-developed flow-banding, flow-folding and autobrecciation and are overlain by massive, crystal-rich dacitic ash-flow tuffs of the Soldados Formation. In the area around the Laguna Yanacocha de Jérez a zone of chaotic megabreccias occurs at the contact between the two formations. This consists of breccias of the Río Blanco Formation which are chaotically mixed with the basal tuffs of the Soldados Formation (see Section 4.7.8.4).

4.7.7.4 Summary and discussion of the Río Blanco Formation: The Río Blanco Formation consists mainly of lavas and volcaniclastic rocks of predominantly andesitic composition, although dacitic and rhyodacitic compositions also occur, particularly in the higher parts of the formation to the south-east of Río Blanco. The volcaniclastic rocks include primary ash-flow tuffs, reworked tuffs, volcanic sandstones and mass-flow breccias.

The Formation is most probably of Early Oligocene age or possibly of basal Late Oligocene age. It is believed to be broadly equivalent in age to the Chanlud Formation.

There is evidence that parts of the unit were deposited subaqueously, and much of the volcaniclastic material transported and redeposited by mass-flow processes. However, the bulk of the unit in the high ground in the south-east, around Río Blanco and farther east, was deposited subaerially. This is probably the youngest part of the unit and contains a higher proportion of dacitic material. Thick lavas are developed in this area and could be the products of domes or extrusions of relatively high-aspect ratio, although more detailed work would be necessary to ascertain their original morphology.

Some of the ash-flow tuffs outcropping to the south-east of Río Blanco resemble those of the overlying Soldados Formation. They are dacitic and contain numerous green fiamme and abundant rounded quartz crystals. To the southeast of Lomo Arquitecto the lavas and breccias of the Río Blanco Formation are overlain by dacitic ash-flow tuffs of the Soldados Formation. At the contact between the two units there is a thick pile of chaotic megabreccias which probably indicates a zone of instability and rapid subsidence at the time of eruption of the Soldados tuffs (see Section 4.7.8.4).

4.7.8 Soldados Formation (O_{Ss})

A thick sequence of subhorizontal to gently dipping, massive crystal-rich dacitic ash-flow tuffs outcrops in the southern part of the Cajas area. The sequence is well-exposed around the settlement of Soldados [6965-96741] from where the formation derives its name. The formation covers a large area to the north of Soldados, extending as far as the Miguir area to the north-west and as far as the southern edge of the Río Mazán drainage basin to the north-east.

4.7.8.1 Stratigraphical relationships and age of the Soldados Formation: To the north and north-east of Soldados the formation rests unconformably upon intermediate lavas of the Chanlud Formation, and to the north-west it overlies lavas of the Río Blanco Formation.

The formation is unconformably overlain by rhyolitic rocks of the Plancharumi Formation in the escarpment to the south-east of Soldados and in the area extending westwards towards Pimo.

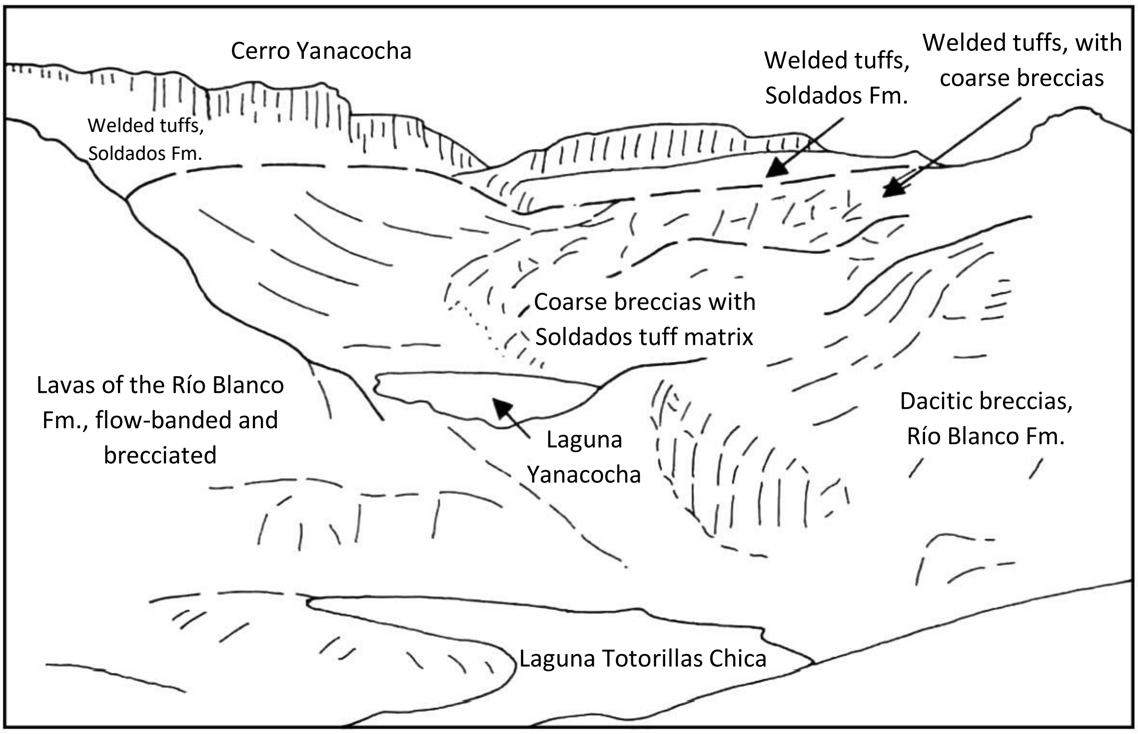


Plate 13. Laguna Totorillas Chica and Laguna Yanacocha [6866-96870]. Viewed from the north-west looking south-east. Dacitic lavas and breccias of the Río Blanco Formation in the foreground, overlain by dacitic ash-flow tuffs of the Soldados Formation in the high ground in the distance. A transitional zone of mixed breccias and tuffs occurs in the middle ground at the base of the Soldados Formation

Plate 14. Breccias at the base of the Soldados Formation (see caption for Plate 15)

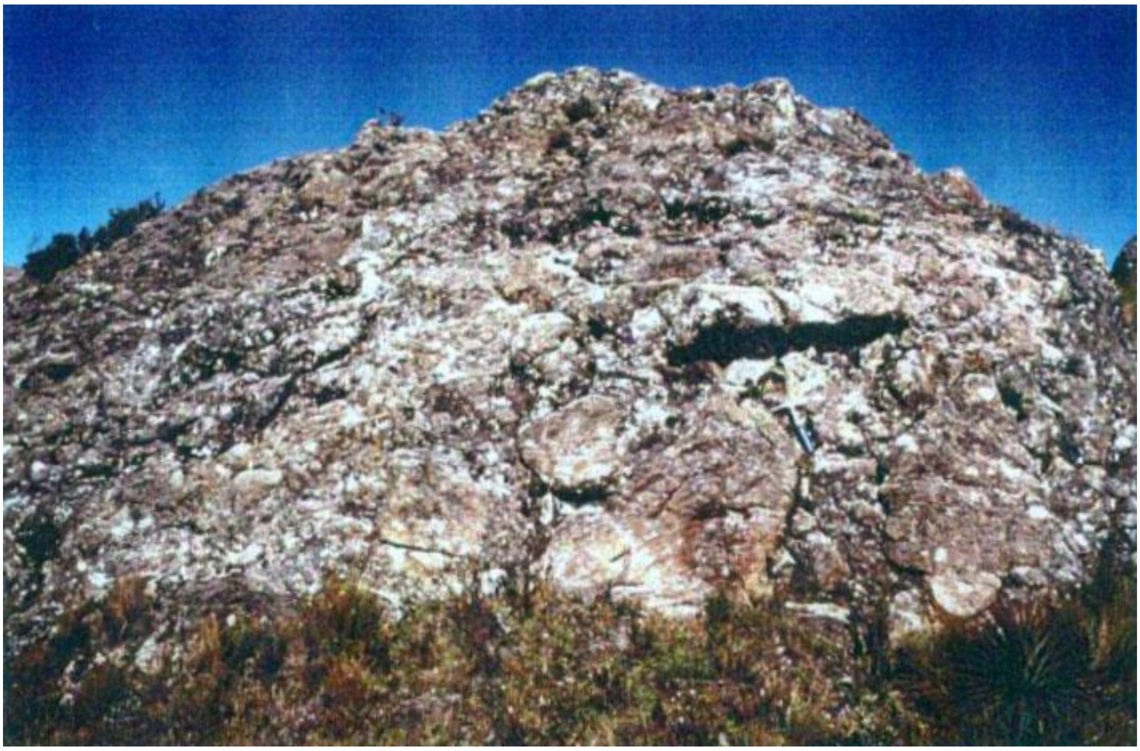


Plate 15. Breccias at the base of the Soldados Formation on the south-west side of Laguna Yanacocha (see Plate 13). The breccias consist of clasts of flow-banded dacite lava from the Río Blanco Formation with an interstitial matrix of crystal-rich tuff of the Soldados Formation

Rivera et al. (1992) report two K/Ar dates of 26 ± 0.8 Ma [6977-96752] and 27 ± 0.7 Ma [6963-96762] from the tuffs near Soldados. During the present study a zircon fission-track date of 29.8 ± 1.2 Ma was obtained from the tuffs exposed at [6907-96793] along the road between Soldados and Angas. These dates indicate that the Soldados Formation is of Late Oligocene age.

4.7.8.2 Description of the tuffs of the Soldados Formation: The Soldados Formation reaches a thickness of more than 400 m in the vicinity of Soldados. At Cerro Palo Blanco [6947-96767], situated 2 km north-west of the settlement, the formation consists of three massive, columnar jointed, ash-flow tuff units that are overlain by a number of thinner ash-flow tuffs which locally contain intercalations of reworked tuffs and volcanic arenites.

The Soldados tuffs are mainly pale grey-green in colour, although pale pink-buff colours are also common and are probably due to oxidation caused by high temperatures at the time of deposition. The tuffs are very rich in crystals. They contain abundant feldspars and rounded quartz crystals, lesser amounts of amphibole, and at a few localities traces of biotite have been observed. Well-developed vitroclastic textures and eutaxitic textures occur throughout the crop of the formation.

A characteristic feature of the tuffs is the ubiquitous presence of abundant green chloritic lapilli which have been flattened to form fiamme. These constitute a significant proportion of the rock (approximately 10-15%) and together with the abundant rounded quartz crystals they distinguish the Soldados tuffs from others within the region. The lapilli and fiamme have diffuse margins which grade imperceptibly into the chloritic matrix of the tuffs. They contain the same phenocryst assemblage as the host tuffs and are poorly vesicular or non-vesicular. They appear to have been plastic or molten at the time of eruption and were strongly flattened and welded on deposition. These distinctive lapilli and fiamme are interpreted as original clots of poorly vesicular magma within the pyroclastic flows, which were initially quenched to form glass that has subsequently been chloritised. All of the fiamme within the Soldados tuffs appear to be formed of these flattened, poorly vesicular clots. Out of the hundreds of localities examined, no strongly vesicular pumice lapilli (i.e. original low-density expanded pumice) have been recognised.

Lithic lapilli and blocks occur throughout the tuffs, but are coarsest and most abundant near the base of the basal flow unit of the formation. They consist mainly of andesite and dacite clasts derived from the underlying lavas of the Chanlud and Río Blanco formations.

Table 7. Chemical analyses of tuffs from the Soldados Formation.

Sample	PND-168	PND-169
SiO_2	68.76	67.92
TiO_2	0.45	0.44
Al_2O_3	15.06	14.49
Fe_2O_3	3.64	3.29
MnO	0.08	0.08
MgO	0.99	0.98
CaO	2.81	2.56
Na_2O	4.00	4.00
K_2O	2.71	3.14
P_2O_5	0.12	0.10
LOI	1.54	2.51
TOTAL	**100.16**	**99.52**

4.7.8.3 Nature of the basal contact of the Soldados Formation: The base of the formation is exposed in the escarpment to the south and west of Laguna Totoracocha [7010-96817], which is situated in the headwaters of the Río Mazán. Here the lavas of the underlying Chanlud Formation cover a very extensive area and dip gently towards the south-east. The lavas are overlain in the escarpment around the southern and western margins of the Mazán drainage basin by columnar jointed tuffs of the Soldados Formation, which along the crest form the prominent line of peaks of Cerro Cotes [6987-96800], Cerro Tinta Cocha [7002-96802] and Soldados [7032-96801].

The basal contact has been examined at two localities in the headwaters of the Río Mazán. At [6974-96813] the uppermost lava of the Chanlud Formation is dacitic and is overlain by a few meters of coarse dacitic breccias with flow-banded clasts up to a metre in size. These coarse breccias are overlain with slight angular discordance by finer epiclastic breccias which are in turn overlain by ash-flow tuffs of the Soldados Formation that are rich in small lithic lapilli. The contact was also examined in the escarpment on the north-west side of the unnamed lake at [6968-96812]. Here andesitic lavas are overlain by welded crystal-rich ash-flow tuffs of the Soldados Formation. The lavas dip south-eastwards at about 20°, whereas the overlying tuffs dip gently towards the south or south-west, indicating the presence of an angular unconformity between the two units. The basal tuffs are massive and contain abundant subangular to subrounded lithic lapilli and blocks of andesitic and dacitic lava up to 0.5 m in size.

The base of the Soldados Formation can also be seen in the high ground to the south and south-east of Miguir [6888-96904]. Subhorizontal to gently dipping dacitic crystal tuffs of the formation rest with angular discordance upon the andesitic tuffs of the Tomebamba Unit in the escarpment to the south-west of Laguna Luspa [6935-96900] and Laguna Canotillos [6940-96885] (Plate 16). Passing south-eastwards the Soldados tuffs overstep onto andesitic and dacitic lavas of the Chanlud Formation. As at other localities, the basal Soldados tuffs in this area contain abundant lithic blocks of andesitic and dacitic lava.

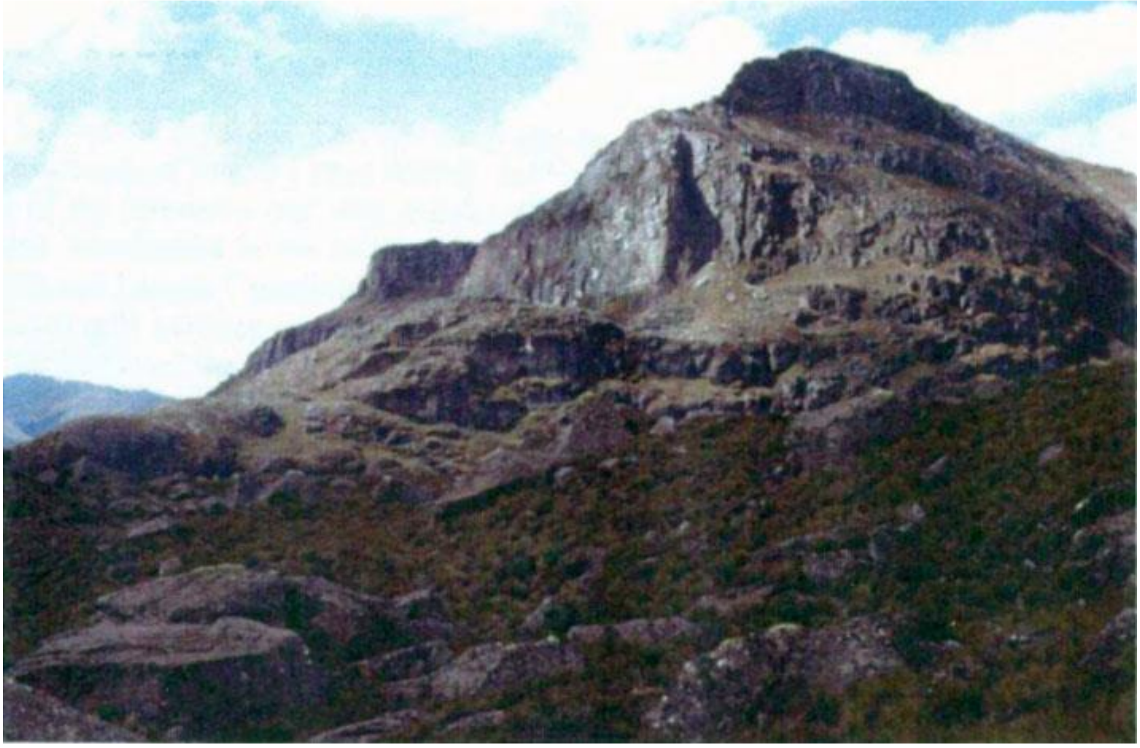


Plate 16. Massive welded dacitic ash-flow tuff of the Soldados Formation, south of Laguna Luspe at [96932-96880] looking south. The tuff is subhorizontal and at least 300 m thick

Plate 17. The headwater valley of the Río Mazán looking south-east. The foreground and middle ground are underlain by south-easterly dipping andesite lavas of the Chanlud Formation, unconformably overlain by dacitic ash-flow tuffs of the Soldados Formation forming the prominent line of peaks on the sky-line

4.7.8.4 Megabreccias in the Laguna Yanacocha-Filo de los Arquitectos área: The most instructive exposures of the basal part of the Soldados Formation occur around Laguna Yanacocha de Jérez [6864-96865] and Laguna Yanacocha [6866-96870] (Plate 13). This locality provides important information regarding the source and mechanism of eruption of the Formation.

In this area the Soldados tuffs rest upon flow-banded and flow-brecciated andesitic and dacitic lavas of the Río Blanco Formation. On the west and south-west sides of Laguna Yanacocha de Jérez the lavas are overlain by a thick, chaotic sequence of extremely poorly sorted breccias composed of flow-banded lava clasts up to 5 m in size (Plates 14 and 15). Some of the breccias have clast-supported fabrics but the majority are matrix-supported mass-flow breccias which have an interstitial matrix of crystal-rich Soldados tuff, characterised by the diagnostic presence of chloritic lapilli and abundant rounded quartz crystals. At [6862-96863] very large rafts of clast-supported andesitic breccias up to 20 metres in size are completely enveloped in the tuffs. Conversely, large rafts of the tuff of similar size are completely enclosed within the breccias. The megabreccias are in turn overlain by the basal ash-flow tuff unit of the Soldados Formation, which consists of a subhorizontal unit of columnar-jointed, welded, crystal-rich dacitic tuff at least 40 metres thick. Lithic clasts occur at the base of this unit and decrease in size and abundance upwards and in a south-easterly direction towards Angas. The intimate mixing of the megabreccias with the basal Soldados tuffs indicates a zone of instability in this area at the time of eruption (see next section).

4.7.8.5 Summary and interpretation of the Soldados Formation: The Soldados Formation comprises several large, massive, crystal-rich dacitic ash-flow tuff units which unconformably overlie the Chanlud and Río Blanco formations and are in turn overlain by the Plancharumi Formation. Radiometric dating indicates a late Oligocene age.

The Formation outcrops over an area of about 300 km^2 and is thought to have an average thickness of between 300 and 400 m. On this basis it has a volume of at least 100 km^3, not allowing for erosion and the volume concealed beneath the Plancharumi Formation. Given that the tuffs are strongly welded and lapilli are poorly vesicular, this volume may be taken as a dense-rock equivalent.

Certain characteristics of the Soldados tuffs are believed to indicate a very rapid eruption, possibly in response to the unroofing of a magma chamber. These include the large volume of material contained within a few flow units, and the abundance of chloritic lapilli and fiamme which make up a large proportion of the tuffs and are interpreted to have been non-vesicular clots of molten or near molten material.

The intimate mixing of the tuffs with megabreccias at the base of the formation in the area between Laguna Yanacocha de Jérez and Filo de los Arquitectos indicates a zone of great instability at the time of eruption of the tuffs. This probably marks the margin of a caldera or depression along which rapid subsidence took place as a result of the evacuation of an underlying magma chamber in response to the eruption of the tuffs. Coarse breccias derived from the Río Blanco Formation to the west collapsed or avalanched eastwards off the margins of the depression as it subsided, and became intimately mixed with the tuffs as they accumulated on its floor. The form of the proposed caldera or depression is impossible to deduce from the available evidence. It may have been circular, although is more likely to have been a trap-door type structure open to the east. It is possible that the subsidence was accommodated along the prominent fault line which runs along the Río Jérez and the east side of Filo de los Arquitectos. The tuffs appear to have ponded within the structure and not to have overflowed its margin to the west.

The underlying Chanlud and Río Blanco formations are predominantly andesitic, but show a trend towards more dacitic and even rhyodacitic compositions over time in the general area between Soldados and Río Blanco. It is therefore possible, that the trend towards more acid volcanism illustrated by the Chanlud and Río Blanco formations culminated in a large-scale explosive event which produced the voluminous dacitic pyroclastic flows of the Soldados Formation.

4.7.9 Cerro Caucay Formation (O_{Scc})

A subhorizontal sheet of massive, crystal-rich rhyolitic ash-flow tuff outcrops in the páramo to the west of Cañar. It caps many of the high peaks of the region and extends almost as far west as Purubín [7127-97171] and as far south-west as the Cordillera del Machángara [7136-97057]. To the north, the tuffs dip steeply north-eastwards into the Cañar valley where they are unconformably overlain by sediments of the Turi Formation. These rhyolitic tuffs are here defined as the Cerro Caucay Formation, being named after the mountain at [7227-97188] where the unit reaches its maximum thickness and is well-exposed in several accessible road sections.

4.7.9.1 Stratigraphical relationships and age of the Cerro Caucay Formation: The tuffs of the Cerro Caucay Formation rest unconformably upon andesite lavas of the Chanlud Formation and are unconformably overlain by sediments of the Turi Formation.

Two zircon fission-track dates of 30.2 ± 1.1 and 27.0 ± 1.0 Ma have been obtained from roadside outcrops in the Cerro Caucay area at [7217-97192] and [7228-97208] respectively. These correspond to a late Early Oligocene-basal Late Oligocene age for the formation.

4.7.9.2 Nature of the tuffs of the Cerro Caucay Formation: The formation consists predominantly of very strongly welded, massive, rhyolitic ash-flow tuffs with well-developed columnar cooling joints. The tuffs are hard, siliceous rocks which are very rich in crystals of quartz, plagioclase, alkali feldspar, biotite and amphibole set in a dark grey to almost black cryptocrystalline to glassy groundmass. The quartz crystals are rounded. Flattened pumice lapilli with tubular vesicles are very common throughout the formation. Small lithic lapilli also occur at all localities, and in the road cuttings on the north-eastern flank of Cerro Caucay at [7228-97120] the tuffs contain abundant lapilli and blocks of amphibole-rich crystal cumulates or cognate xenoliths.

Weathered surfaces are pale grey to buff-pink in colour. Vitroclastic textures are clearly discernible in hand specimen and in thin section at all localities. Strong eutaxitic textures occur throughout, and ultra-welded zones showing evidence of rheomorphism in the form of flow-banding and flow-folding are common. In a number of localities strongly welded zones are preserved as original obsidian.

Dacitic tuffs also occur within the formation, but are volumetrically much less important than the rhyolitic tuffs and only occur in a relatively restricted area on the north-east flanks of Cerro Caucay and on the north side of the Río Cañar. In both of these areas they are thought to be at the top of the formation and are gradational into the underlying rhyolitic tuffs. They are pale pink to buff in colour, intensely welded and contain abundant crystals of amphibole and feldspar, but unlike the rhyolitic tuffs contain few or no crystals of quartz and biotite. The dacitic tuffs on the north-east flank of Cerro Caucay also contain abundant blocks and lapilli of amphibole and amphibole-rich crystal cumulate material.

Six chemical analyses of tuffs from the Cerro Caucay area are presented in Table 8. When recalculated on a water free basis five of the analyses are of rhyolitic composition and one is of dacitic composition. Sample PND-1028 is an obsidian collected from an intensively welded zone. It is strongly hydrated but when the analysis is recalculated on a volatile free basis it contains 76.26% SiO_2, which illustrates the very siliceous nature of the original volcanic glass. The dacitic sample (PND-1019) is rich in crystals and cognate xenoliths of amphibole, the latter accounting for about 20% of the rock. The dacitic composition probably reflects the presence of a high proportion of amphibole inclusions in the whole-rock, whereas the matrix of the tuff is probably rhyodacitic.

Table 8. Chemical analyses of tuffs from the Cerro Caucay Formation

Sample	PND-994	PND-1015	PND-1017	PND-1019	PND-1028	PND-1035
SiO_2	70.44	74.81	72.89	63.75	72.40	74.12
TiO_2	0.33	0.2	0.32	0.69	0.23	0.20
Al_2O_3	13.47	12.69	13.02	14.53	12.13	12.68
Fe_2O_3	2.44	1.68	1.7	5.63	1.39	1.57
MnO	0.07	0.03	0.04	0.09	0.04	0.03
MgO	0.75	0.45	0.49	2.41	0.33	0.31
CaO	2.19	1.20	1.70	3.05	1.10	1.01
Na_2O	2.85	3.17	3.17	4.08	3.33	2.59
K_2O	3.61	4.23	3.92	3.08	3.96	4.83
P_2O_5	0.06	0.04	0.04	0.11	0.03	0.04
LOI	3.46	1.28	1.35	2.48	4.38	2.31
TOTAL	**99.67**	**99.78**	**98.64**	**99.9**	**99.32**	**99.69**

4.7.9.3 The Cerro Caucay Formation in the type area: The formation is exposed in sections along the road between Purubín [7125-97172] and Cañar, and is particularly well-displayed along the aqueduct around the western and northern flanks of Cerro Caucay between Matan [7205-97165] and Jirincay [7255-97178]. A thickness of about 450 metres is estimated for the formation in this section.

The basal contact of the formation with the underlying andesite lavas of the Chanlud Formation is exposed along the aqueduct immediately to the south and north of Matan and Curiucu. It is subhorizontal but gently undulating.

Northwards the aqueduct passes into the main body of the formation. The cuttings of the aqueduct provide continuous exposure through unweathered, dark-grey to almost black glassy crystal-rich rhyolitic ash-flow tuffs with prominent columnar cooling joints. In thin section these tuffs are seen to be intensely welded (ultra-welded). On weathered joint faces extreme eutaxitic textures are visible and flow-banding and flow-folding indicate zones of rheomorphism. The formation is well-exposed in the cliffs and crags above the aqueduct on the western flanks of Cerro Caucay. Here the tuffs display very well-developed, large-scale, columnar cooling joints. The cliffs were not examined during the survey, but visible breaks within the sequence suggest the presence of two or possibly three distinct flows or cooling units.

The tuffs exposed along the aqueduct section on the west side of Cerro Caucay are subhorizontal with near vertical columnar cooling joints, but at the prominent bend in the aqueduct at [7225-97211] the eutaxitic texture abruptly changes attitude and becomes steeply inclined (between 45 and 90°) towards the north and north-east and the columnar joints show a concomitant change in attitude (being approximately perpendicular to the eutaxitic texture). Passing south-eastwards along the aqueduct from this point the tuffs change in character. Between [7225-97205] and [7249-97195] they are pale pink-buff in colour and contain abundant amphibole and feldspar crystals with only minor quartz and biotite. They are extremely welded and contain lapilli and fiamme of pumice with tubular vesicles. The most striking feature of these tuffs apart from their pink colour is the presence of abundant lapilli and blocks of amphibolite or amphibole-rich crystal cumulate material. These range from less than a centimetre up to a metre in size and in places account for up to 20% of the rock by volume. Gamma-ray spectrometer readings indicate more basic compositions in this sector, and this is supported by the dacitic chemical analysis of sample PND-1019. Based on the orientation of eutaxitic textures, the dacitic tuffs within the aqueduct section are believed to overlie the rhyolitic tuffs, although the contact between the two appears to be gradational.

One additional feature to note is that, in the aqueduct section on the north-east flanks of Cerro Caucay around [7236-97207] the tuffs contain significant amounts of fine-grained amethystine quartz. Similarly, amethystine quartz is present within the tuffs lower on the north-eastern flanks in the road section around [7240-97216]. The juxtaposition of these two localities suggests that amethystine quartz may occur in a broad zone.

4.7.9.4 The Cerro Caucay Formation on the north side of the Río Cañar: To the north-west of Cañar the Río Cañar flows through a gorge incised within the tuffs of the Cerro Caucay Formation. The massive and columnar jointed tuffs outcropping in the walls of the gorge have been examined on the north side of the river around Loma de Burán, Loma Inganilla and in the cliffs of the tributary valley of the Río San Antonio.

Here the tuffs dip beneath the sediments of the Turi Formation. They have a strong eutaxitic texture which dips at between 25 and 30 degrees towards the north-east, parallel to the surface dipslope of Loma de Burán. The uppermost tuffs in this section are pale buff to pink dacitic tuffs with well-developed vitroclastic textures. They contain abundant crystals of feldspar and hornblende, but few crystals of quartz.

Passing down the section to lower levels within the gorge, the tuffs become noticeably more acid and rhyolitic in composition and contain abundant quartz crystals and lithic clasts. Gamma-ray scintillometer readings also indicate that the composition of the tuffs changes systematically from being dacitic at the top of the section to rhyolitic at lower levels.

4.7.9.5 Other sections through the Cerro Caucay Formation : The Cerro Caucay Formation has been examined in a number of other sections and localities. These include the areas of Jatunloma-Cerro Trojecharina [7185-97100], Cerro Caparina [7146-97128], Cerro Saramontón [7131-97114] and the Cordillera del Machángara [7137-97057]. In all these areas the formation consists of massive, columnar jointed, strongly welded rhyolitic ash-flow tuffs which contain abundant crystals of quartz and feldspar and accessory biotite and hornblende.

4.7.9.6 Summary and discussion of the Cerro Caucay Formation: The Cerro Caucay Formation consists mainly of massive, columnar jointed, intensely welded, crystal-rich rhyolitic ash-flow tuffs which contain abundant crystals of quartz, feldspar, biotite and amphibole. It rests unconformably upon andesite lavas of the Chanlud Formation and has yielded fission-track dates of late Early Oligocene to basal Late Oligocene age.

The Formation reaches its thickest development of about 450 m at Cerro Caucay. Here it is ultra-welded and has zones of flow-banding and flow-folding which indicate rheomorphism. Locally, zones of intense welding are preserved as original obsidian. Prominent breaks in the cliffs of Cerro Caucay suggest that several flows or cooling units are present.

Observations from the aqueduct section on the north-east side of Cerro Caucay and from the section on the north side of the Río Cañar around the Río San Antonio indicate that the tuffs are compositionally zoned. Although the formation is overwhelmingly rhyolitic in composition and normally contains abundant quartz and biotite crystals, the uppermost tuffs in these two areas are rhyodacitic and dacitic and contain abundant amphibole but few quartz and biotite crystals. These dacitic tuffs also contain abundant lapilli and blocks of amphibole or amphibole-rich crystal cumulate material which locally account for up to 20% of the rock by volume.

The available evidence suggests that the tuffs of the formation were erupted rapidly from a differentiated and compositionally zoned magma chamber. In such a model, rhyolitic ash-flows would initially have been erupted from the more fractionated upper parts of the chamber, followed by less fractionated rhyodacitic and dacitic magma from lower in the chamber. The rapid evacuation of the chamber may have resulted in disruption of crystal cumulates from lower in the chamber or from its side walls, which were incorporated or entrained into the less fractioned magma as amphibole-rich cognate xenoliths and xenocrysts that were brought to the surface and erupted with the dacitic tuffs.

4.7.10 Plancharumi Formation (O_{Sp})

A distinctive sequence of white-weathering, poorly lithified, rhyolitic pumiceous tuffs, pumice-lapillistones, breccias, lavas and well-bedded sandstones, siltstones, mudstones and fine ash-tuffs outcrops along the southern margin of the area around Soldados and Pimo. This sequence is here named the Plancharumi Formation, after the prominent escarpment of Cerro Plancharumi to the south of Soldados.

4.7.10.1 Stratigraphical relationships and age of the Plancharumi Formation: The Plancharumi Formation rests unconformably upon the Soldados Formation and is in turn unconformably overlain with angular discordance by the Jubones Formation and the Quimsacocha Formation.

A zircon fission-track date of 25.7 ± 1.1 Ma was obtained from a primary air-fall tuff (PND-1438) within the formation near the top of the ridge at [6887-97012]. This corresponds to a Late Oligocene age.

4.7.10.2 The Plancharumi Formation in the type area: The escarpment of Cerro Plancharumi exposes a well-stratified sequence of rocks approximately 350 m thick which dips gently southwards with inclinations of up to 10°. A section was examined through this sequence about 3 km east of Soldados, starting on the floor of the valley at Hacienda Capulí [7009-96760] and extending to the top of Cerro Plancharumi [6990-96737].

The lower part of the escarpment is composed of brown to pinkish brown, welded dacitic ash-flow tuffs of the Soldados Formation. At an altitude of about 3500 m these are overlain by relatively soft, white-weathering rhyolitic volcaniclastic rocks of the Plancharumi Formation, which extend up to the summit of the escarpment. The deep weathering of these deposits produces a distinctive pillared topography which can be seen along the upper part of the escarpment.

The lowest part of the formation in the Cerro Plancharumi escarpment is a white rhyolitic pumice lapilli ash-flow tuff approximately 50 metres thick. It is poorly lithified and unwelded and contains a high proportion of undeformed, coarse lapilli and blocks of pumice, including tubular pumice, which are distributed uniformly throughout the flow unit. Coarse, poorly-sorted, rhyolitic debris-flow breccias overlie this tuff. These are polymictic but contain abundant clasts of flow-banded rhyolite lava up to a metre in diameter. The breccias pass up into a bedded sequence approximately 160 m thick, which consists of white-weathering, pumice-rich lapillistones, tuffaceous sandstones, fine tuffs, microbreccias and breccias. Pumice clasts are undeformed and have vesicles that are still partially hollow, and as a result the pumiceous rocks have relatively low densities. The sandstones form beds up to 1.5 m thick, some of which exhibit planar bedding and less commonly low-angle cross-stratification. Thin beds of cream-coloured fine-ash tuffs, laminated siltstones and silty mudstones are intercalated throughout the bedded sequence. The sediments are overlain by a pale pink to pale green-coloured rhyolitic ash-flow tuff approximately 20 m thick. This has a strong eutaxitic texture and contains lithic clasts of flow-banded rhyolite. At the top of the escarpment the sequence is capped by two massive, crystal-poor ash-flow tuffs approximately 70 m thick. These are rhyolitic in composition but weather to a deep red-brown colour. The lower tuff is unwelded and finely vesicular. In thin section it exhibits excellent vitroclastic textures composed entirely of undeformed, delicate cuspate shards and pumice lapilli. In contrast, the upper tuff is an ultra-welded, dense, glassy rock with a very strongly developed eutaxitic texture. This welded tuff caps the escarpment of Cerro Plancharumi and forms an extensive dip-surface which slopes gently southwards into the basin of the Río Bermejo.

On the south side of the Río Bermejo drainage basin, the welded tuff capping the dip-slope is overlain by a thin sequence of waterlain rhyolitic pumiceous tuffs, fine-ash tuffs, tuffaceous siltstones and sandstones. These are exposed around the Quebrada Quinde Huilo [96965-96706] where they are overlain unconformably by andesite lavas and breccias of the Quimsacocha Formation.

The total thickness of the Plancharumi Formation in the Cerro Plancharumi – Río Bermejo section is approximately 400 m.

4.7.10.3 The Plancharumi Formation in the Pimo area: To the west of Cerro Plancharumi the formation is almost completely concealed by an extensive cover of peat in the Río Quingoyacu drainage basin. Farther west, however, it is exposed in a low ridge which strikes north-eastwards from near Pimo [6850-96705] to the confluence of Quebrada Curiquingue and Quebrada Alacena [6887-96726]. This ridge has a north-westerly facing escarpment and a gentle dip-slope which is inclined approximately 15° towards the south-east.

The lowest exposures in this area consist of well-bedded, pale buff coloured sandstones, siltstones and fine tuffs which outcrop around the confluence of Quebrada Curiquingue and Quebrada Alacena. These are overlain by rhyolitic lavas, breccias, pumice lapillistones, pumice lapilli tuffs and fine-ash tuffs. The lavas are well-exposed in the escarpment along the south side of the track leading to Pimo. They are intensely and uniformly flow-banded, and in a few places zones of original obsidian are preserved. To the east of the ridge, intensely flow-banded, flow-folded and flow-brecciated rhyolites are exposed along the length of the Quebrada Can Can. Passing up the succession, the lavas are overlain by cream-coloured rhyolitic pumice-lapilli tuffs, lapillistones and pumiceous breccias of pyroclastic flow origin. These are massive and poorly stratified, and in places medium- to large-scale cross-stratification is also preserved. The pumice lapilli are undeformed and as a result the tuffs have relatively low densities. Rhyolite lava clasts occur within these pyroclastic flow deposits and in rare examples are preserved as original obsidian. Well-bedded fine-ash tuffs and dust tuffs occur near the top of the ridge [6887-97012]. These contain abundant accretionary lapilli and are interpreted as primary air-fall tuffs. One such tuff at this locality (PND-1438) yielded a zircon fission track date of 25.7 ± 1.1 Ma. The tuffs are overlain by intensely flow-banded rhyolite lavas which cap the ridge.

To the west of Pimo the formation is exposed in the ridge of Cascajo [6810-96690]. Here it consists of rhyolitic pumiceous tuffs and rhyolite autobreccias, which are overlain by the Jubones Formation.

4.7.10.4 Chemical composition of the Plancharumi Formation: The volcanic rocks of the Plancharumi Formation are obviously acid, but because they are strongly weathered and the lavas are recrystallised their original composition is not entirely certain. However, obsidians are preserved at a few localities and should reflect original compositions. Two analyses of obsidians from the formation are presented in Table 9. One sample (PND-1616) was taken from a lava [6860-96709] and the other (PND-1436) is a composite sample of obsidian clasts collected from a pumice lapilli ash-flow tuff at [6890-96710]. The analyses indicate rhyolitic compositions. The lava sample (PND-1616) contains only 70.39% SiO_2, but it is strongly hydrated and when the analysis is recalculated on a water free basis it contains 74.16% SiO_2.

4.7.10.5 Summary and interpretation of the Plancharumi Formation: The Plancharumi Formation is of Late Oligocene age.

The occurrence of well-bedded sandstones, laminated siltstones, mudstones and very fine tuffs is taken as evidence for deposition in a lacustrine or fluvio-lacustrine basin. Large volumes of rhyolitic products were erupted and deposited within the basin. These include pumiceous pyroclastic flow deposits, air-fall tuffs and rhyolite lavas and breccias. Much of the volcaniclastic material was reworked and redeposited by mass-flow processes.

Table 9. Chemical analyses of obsidians from the Plancharumi Formation

Sample	PND-1436	PND-1616
SiO_2	75.79	70.39
TiO_2	0.22	0.24
Al_2O_3	13.29	13.38
Fe_2O_3	1.53	2.47
MnO	0.04	0.08
MgO	<0.01	0.18
CaO	1.32	1.96
Na_2O	3.12	2.71
K_2O	3.90	3.48
P_2O_5	0.04	0.04
LOI	0.93	5.08
TOTAL	**100.18**	**100.01**
Ba	913	874
Ce	27	37
Co	<5	<5
Cr	<4	4
Cs	<2	2
Hf	9	10
La	21	20
Nb	10	9
Nd	20	26
Ni	5	4
Rb	110	156
Sc	5	12
Sm	8	<3
Sr	129	172
Ta	<2	<2
Th	3	1
U	2	4
V	<5	9
Y	30	33
Zr	226	232

The vesicular nature of some of the ash-flow tuffs indicates that the ashes were wet at the time of eruption or deposition. The presence of accretionary lapilli within the finer tuffs indicates deposition from subaerial eruption columns or ash-clouds (associated with pyroclastic flows) and also suggests relatively wet conditions at the time of eruption. The unwelded, vesicular, (red-brown) ash-flow tuff near the top of the Plancharumi escarpment was obviously wet when deposited, and its very fine vitroclastic texture is good evidence for a strongly explosive eruption. The occurrence of very fine tuffs interstratified with coarse pumiceous rocks also probably indicates strongly explosive activity. The presence of abundant pumice, together with evidence of water being involved in strongly explosive eruptions, suggests that much of the activity was hydrovolcanic, and possibly of phreatoplinian style. The large-scale cross-bedding within some of the pumiceous tuffs and lapillistones could be the result of base-surges which are typically associated with hydrovolcanic activity.

In summary, the Plancharumi Formation is interpreted as having accumulated within a lacustrine or fluvio-lacustrine environment into which rhyolitic pumice-flows and ash-flows were erupted. Interaction with water appears to have resulted in strongly explosive phreatomagmatic activity, producing very fine tuffs, and wet ash-flows and ash-falls, possibly accompanied by base-surge activity.

Rhyolites were extruded (and possibly intruded) into these deposits. The absence of rhyolite lavas in the Soldados-Plancharumi area and their presence farther west are taken to indicate that an eruptive centre existed in the Pimo area. The orientation of flow-banding within the rhyolites suggests that their aspect ratios were not high, and that flows were probably more akin to coulees in form. However, the presence throughout the formation of coarse rhyolitic autobreccias and debris-flow breccias composed of flow-banded lava clasts, suggest that steep-sided flows or domes may also have been extruded.

4.7.11 Jubones Formation (M_{Sj})

The Jubones Formation consists of a single, large-volume, crystal-rich rhyolitic ash-flow tuff which outcrops along the extreme southern margin of the area, in the páramo to the south and south-east of Pimo [6830-96700].

Although there is a restricted outcrop within the mapped area, the Formation is very extensive within the area of the adjacent map sheet to the south (BGS-CODIGEM, 1998c). Here it has been examined in detail by Pratt et al. (1997), who define the type section along the road to the east of Río Minas [6805-96320].

4.7.11.1 Stratigraphical relationships and age of the Jubones Formation: Within the mapped area the Jubones Formation rests with angular unconformity upon the Plancharumi Formation and older undifferentiated rocks of the Saraguro Group. It is overlain with strong discordance by andesitic lavas and breccias of the Quimsacocha Formation.

Two radiometric dates have been obtained from the Jubones Formation in the area to south of the present study. Pratt et al. (1997) report a K/Ar age of 22.76 ± 0.97 Ma from the formation near Santa Isabel, and a zircon fission-track age of 23.0 ± 2.2 Ma has been obtained from tuffs near Oña (Hungerbühler, in prep.). These dates indicate that the Jubones Formation has a basal Miocene age.

4.7.11.2 Description of the Jubones Formation within the area: The best exposures of the formation within the mapped area occur in the hill immediately to the south-east of Pimo around [6840-96690], and along the path leading south-west from Pimo to the ridge of Cerro Cascajo. Here the formation consists of a massive, columnar jointed, rhyolitic ash-flow tuff about 200 m thick. It is very rich in coarse crystals of feldspar, quartz and biotite, and contains flattened fiamme which impart a strong eutaxitic texture to the rock. The crystals account for up to 50% of the rock by volume and are supported within a pale brown to buff glassy matrix which is strongly welded.

4.7.11.3 Summary and discussion of the Jubones Formation: The Jubones Formation consists of a very crystal-rich rhyolitic ash-flow tuff of basal Miocene age. Little can be inferred about the formation within the mapped area because of its restricted distribution and poor exposure.

According to the studies of Pratt et al. (1997), the formation crops out over an area of 2700 km^2 and reaches a thickness of at least 500 m in the region to the south. Pratt et al. estimate a minimum volume of 350 km^3 for the tuff, which probably represents a single, major pyroclastic eruption, which probably gave rise to the formation of a large caldera. Facies and thickness variations indicate the source caldera was probably centred approximately 20 km to the south of the mapped area, in the vicinity of the Río Minas type section.

4.7.12 Puñay Unit (O?M?$_{Spñ}$)

The Puñay Unit is composed of amphibole-bearing andesitic lavas, breccias, volcanic sandstones and siltstones, which include red beds. The unit crops out in a NE-trending belt between Chanchán [7284-97496] and Javín [7024-97269] and is named after the prominent mountain of Cerro Puñay [7258-97426] which is situated in the central part of the belt.

Several rock sequences make up the unit. At the scale of the survey these could not be mapped separately with any degree of confidence because of structural complexities combined in some areas with poor exposure. The sequences do however share a number of common features which justify their inclusion in the same unit. These include continuity of outcrop, similarities in composition and mineralogy between the clastic rocks and the lavas of the unit, and the presence of red beds.

4.7.12.1 Stratigraphical relationships and age of the Puñay Unit: The Puñay Unit is the least understood lithostratigraphical unit of the area, in terms of its stratigraphical position. This is partly because contact relationships with other units are not clear due to poor exposure and structural complexities, and also because no radiometric dates have been obtained from the unit.

The unit rests upon, and is faulted against the Ocaña Formation. Outcrop patterns portrayed on the map also imply that the Puñay Unit rests unconformably upon the Tomebamba Unit and Chanlud Formation, although actual contacts have not been observed with these units. The rocks of the unit are folded along NE-trending axes and unconformably overlain by subhorizontal strata of the Turi and Cisarán formations. These relationships indicate that the age of the Puñay Unit lies somewhere between the Early Oligocene and Late Miocene.

Two K/Ar dates of 21.0 ± 1.0 Ma and 27 ± 0.9 Ma were attributed to the Puñay Unit in the description on the published geological map which accompanies this report (BGS-CODIGEM, 1998b). These dates were obtained by Egüez et al. (1992) from rocks originally assigned to the Alausí Formation, a stratigraphical term not used in the present work. It has subsequently been realised that a mistake was made on the map and that the dates may not necessarily pertain to the Puñay Unit. The dated rocks actually occur in an isolated fault-bounded outlier to the north of the Puñay Unit, and were portrayed on the map as undifferentiated Saraguro Group. They are however very similar to the rocks of the Puñay Unit (consisting of andesitic lavas, volcanic sandstones and red and purple siltstones) and occur in an analogous structural position. They could therefore be correlated with the Puñay Unit, although in the absence of contact relationships such a correlation must remain enigmatic. If correlation of the Puñay Unit with the (dated) undifferentiated Saraguro Group outlier to the north is valid, then the unit is probably of Late Oligocene or Early Miocene age.

Alternatively, the Puñay Unit may not be part of the Saraguro Group, and could be younger. The sediments of the unit are very similar in character to those of the Miocene Ayancay Group of the Cuenca Basin (Section 4.8). On reflection, and in the absence of radiometric dates, this correlation is now preferred to that portrayed on the published map.

4.7.12.2 Volcaniclastic rocks of the Puñay Unit to the north-east of Huigra: Andesitic volcaniclastic rocks outcrop in the north-east of the unit. These are exposed in a section along the railway line in the Chanchán valley between Huigra [7247-97475] and Chanchán [7285-97496]. They consist of grey-green and purple-red, medium- to thick-bedded volcanic sandstones and andesitic breccias with thin beds of purple-red siltstone. The sandstones are feldspathic and also contain hornblende. They are poorly sorted, medium- to coarse-grained and include graded beds and massive beds with matrix-supported angular clasts and rounded pebbles of andesite and rip-up clasts of siltstone. Andesitic debris-flow breccias and sandstones containing large pieces of carbonised wood occur immediately to the east of Chanchán. The rocks of this section are interpreted as high density turbidities and debris-flow breccias derived from an andesitic volcanic source.

The road from Chanchán to Penipales [7300-97530] exposes similar rocks. Thin- to medium-bedded turbiditic volcanic sandstones and siltstones outcrop in the road at [7283-97502], and massive pebbly volcanic sandstones at [7285-97510]. The latter show evidence of slumping and emplacement by mass-flow, and contain andesite clasts and large fragments of wood preserved as hard, shiny coal. Coal is also reported to have been mined nearby in the vicinity of Sibambe.

4.7.12.3 Volcaniclastic rocks and lavas in the Cerro Puñay-General Morales area: Andesite lavas, breccias and volcanic sandstones outcrop within the central part of the Puñay Unit belt. These appear to overlie the sediments of the Huigra-Chanchán area (described in the previous section).

In the ground to the north of General Morales [7200-97341] the unit crops out in a large NE-trending syncline with an axis that passes through El Tocte [7180-97390]. The rocks of the south-eastern limb of this structure give rise to a well-featured series of scarps and dipslopes. Sections were examined through these rocks along the road between General Morales and Hierba Buena [7175-97362], and along the track between Llagos [7240-97390] and the bridge over the Río Angas [7179-97416]. The rocks in this area consist mainly of well-stratified khaki green to pale brown, medium- to coarse-grained volcanic sandstones and microbreccias, with thin partings of pink to red coloured siltstone. The sandstones are poorly sorted, feldspathic and rich in hornblende. They exhibit graded bedding, planar bedding, low-angle cross-bedding and ripple-cross lamination, and are interpreted as proximal turbidites (T_{a-d}) which were derived from an andesitic source. Silicified wood was observed in the base of one massive sandstone at [7174-97365]. In the western part of the Llagos-Río Angas section these sediments pass up into a massive sequence of hornblende andesite lavas and breccias.

At Cerro Puñay the succession dips uniformly to the south-west at about 45° and has a thickness of about 3000m. Here, and in the road section west of Huigra [7245-97470] it consists of a monotonous sequence of hornblende andesite lavas and breccias with subordinate tuffs and volcanic sandstones.

4.7.12.4 The Puñay Unit between Javín and Chontamarca: In the south-west, the Puñay Unit consists of siltstones, mudstones, volcanic sandstones, tuffs, breccias and conglomerates, with rare andesite lavas. These appear to underlie the lavas and coarser volcaniclastic rocks of the General Morales-Cerro Puñay area to the north-east (described in the previous section). They have been examined in sections along the road between Javín and San Antonio de Gualleturo, and along the main road between Javín and Chontamarca.

The road between Javín [7017-97267] and San Antonio de Gualleturo exposes purple and red-brown siltstones, mudstones and volcanic sandstones with beds of mass-flow conglomerate and breccia of andesitic composition. The sequence is tightly folded along NE-trending axes and on the north side of the Río Cañar it is strongly sheared. This shearing is associated with splay faults of the Bulubulu Fault System. Where it is less deformed, the sequence is well-stratified. The volcanic sandstones are dirty and poorly sorted, and include massive debris flows with matrix-supported pebbles and angular clasts of hornblende andesite.

4.7.12.5 Summary and discussion of the Puñay Unit: The Puñay Unit rests upon, and is faulted against the Ocaña Formation and appears to rest unconformably upon the Tomebamba Unit and Chanlud Formation. The rocks of the unit are folded along NE-trending axes and unconformably overlain by subhorizontal strata of the Turi and Cisarán formations. The age of the unit is unknown, but by analogy with similar rocks farther north, which have been radiometrically dated, it could be of Late Oligocene or Early Miocene age. Alternatively, it could be a correlative of the Early to Middle Miocene Ayancay Group.

The lower parts of the unit are exposed in the north-east and south-west and consist of green and purple-red siltstones, sandstones and breccias, which show evidence of deposition by mass-flow. These pass up into a thick monotonous sequence of hornblende andesite lavas, breccias and sandstones in the Cerro Puñay area.

The unit is in excess of 3 km in thickness and appears to have accumulated rapidly in a basin which was proximal to an andesitic source. The location of this thick sequence, juxtaposed against a splay fault of the Bulubulu Fault, may possibly indicate deposition within a pull-apart basin, formed in response to strike-slip movement along the fault system.

4.7.13 Undifferentiated Saraguro Group (E-M$_S$)

Two areas have been designated as undifferentiated Saraguro Group on the map. These include a small faulted inlier in the north, and a larger area around Chaucha in the south-west.

4.7.13.1 Undifferentiated Saraguro Group in the north of the area: A small faulted inlier of red and purple siltstones, volcanic sandstones and andesite lavas occurs in the north of the area in the vicinity of Gauhín Grande [7295-97678]. This is faulted against the Pallatanga and Yunguilla units and is overlain unconformably by the Cisarán Formation.

These rocks are exposed on the road between Alausí and San Francisco de Multitud between [7283-97620] and [7285-97649]. Egüez et al. (1992) originally included them in the Alausí Unit, a term not used in the present study, and obtained two K/Ar dates of 21 ± 1.0 Ma and 27 ± 0.9 Ma, reputably from an andesite lava.

Although these rocks are designated undifferentiated Saraguro Group on the published map, they are probably equivalent to the Puñay Unit which outcrops in a similar structural position to the south (Section 4.7.12). As discussed in Section 4.7.12.1, the Puñay Unit could be younger than the Saraguro Group and possibly a correlative of the Ayancay Group (Section 4.8).

4.7.13.2 Undifferentiated Saraguro Group in the Chaucha area: The largest area of undifferentiated Saraguro Group occurs in the south-west around Chaucha. These rocks have only been examined along the road between Angas and Chaucha, and in the Río Chaucha between Chaucha and La Iberia. In both sections they consist of acid volcanic rocks that have been hornfelsed and hydrothermally altered by the Chaucha batholith.

The most instructive section is seen along the road between Chaucha and Angas. Finely banded green-grey rocks outcrop in the road near the margin of intrusion at Chaucha, as for example around [6792-96790]. Previous workers classified these as metamorphic rocks, but in thin section they are clearly identifiable as flow-banded microporphyritic dacitic or rhyodacitic lavas. Between this locality and the Quebrada Jérez [6821-96806] the strata dip to the north-west and consist of crystal-rich dacitic ash-flow tuffs, mass-flow breccias and volcanic sandstones with thin beds of white tuffaceous siltstone. The mass-flow breccias contain clasts of siltstone, mudstone and volcanic lithologies, supported within tuffaceous sandstone matrices.

On the south-east side of the Quebrada Jérez the road section passes through rhyolitic rocks. Between the quebrada and the prominent bend at Loma Chilchiloma [6815-96782] these consist of intensely flow-banded rhyolite lavas and welded rhyolitic ash-flow tuffs with strong eutaxitic textures, which contain crystals of quartz, feldspar and traces of biotite. From the bend in the road eastwards as far as [6842-96780] the section consists of rhyolitic and rhyodacitic tuffs, lavas and breccias with intercalations of reworked volcanic sandstones. The lavas are flow-banded and exhibit spherulitic recrystallisation. The breccias include poorly bedded mass-flow breccias which contain rare clasts of obsidian.

Between [6842-96780] and Angas the sequence is less-well exposed and hydrothermally altered. It mainly consists of more andesitic and dacitic crystal tuffs with mass-flow breccias and thin beds of tuffaceous sandstone.

Although mapped as undifferentiated Saraguro Group, the rhyolitic rocks near Chaucha are very similar to those of the Chulo Unit of the Cajas area to the north. Similarly, the intermediate andesitic and dacitic tuffs near Angas also resemble tuffs within the Filo Cajas Unit. The strata of the Angas-Chaucha road section are folded and generally dip north-westwards, and are unconformably overlain by younger subhorizontal units such as the Río Blanco Formation and Soldados Formation. In this respect they also resemble the Chulo Unit and Filo Cajas Unit.

From the available evidence it is concluded that the undifferentiated Saraguro Group in the Chaucha area is probably equivalent to the Chulo Unit and possibly the Filo Cajas Unit, which are of Eocene age.

4.8 Ayancay Group (M_A)

The Ayancay Group forms part of the sedimentary sequence of the Cuenca Basin situated along the eastern margin of the mapped area.

The term Ayancay Group was first used by a project of the United Nations Development Programme which undertook an assessment of the coal deposits of the Cuenca Basin (UNDP, 1969).

Within the Cuenca Basin the group consists of the Santa Rosa and Mangán formations (Bristow and Hoffstetter, 1977; Bristow and Parodiz, 1982). These are of fluvial origin and are composed predominantly of an alternating sequence of sandstones, green and red mudstones and siltstones, with rare tuffs, beds of coal and conglomerates.

The Ayancay Group rests unconformably on the Saraguro Group and is overlain by the Turi Formation. Deposition of the Ayancay Group began some time after 18 Ma and finished at about 10 Ma (Hungerbühler, 1997).

4.9 Turi Formation (M_T)

The Turi Formation was defined by Erazo (1957) and consists mainly of fluvial sedimentary rocks which are confined to the Cuenca Basin and its extensions.

The rocks of the formation have not been studied in detail by the present survey because they mainly fall outside the mapped area. For detailed descriptions the reader is referred to Bristow and Parodiz (1982) and Steinmann (1997b).

Within the mapped area the formation crops out to the south-west of Turi [7215-96768] near Cuenca, and in the ground between Cañar and Suscal.

In the Cuenca-Turi area the rocks of the formation are at least 300 m thick. They consist principally of horizontally stratified, poorly lithified, coarse conglomerates and breccio-conglomerates of andesitic composition, with intercalations of pale-coloured tuffaceous sandstones and tuffaceous siltstones.

In the Cañar-Suscal area the formation consists of subhorizontal to gently dipping conglomerates, breccio-conglomerates and poorly consolidated, pale-coloured siltstones, sandstones, tuffs and diatomites.

The Turi Formation rests unconformably upon the Saraguro Group and is overlain by the Quimsacocha Formation. It was previously considered to be of Pliocene age (Bristow and Parodiz, 1982), but new fission-track dates indicate a Late Miocene age of 8-9 Ma (Hungerbühler and Steinmann, 1996; Steinmann, 1997b).

4.10 Turupamba Formation (M_{Tu})

The Turupamba Formation occurs in two very small areas on the extreme southern margin of the map at [6895-96684] and [6826-96684].

The formation was defined by Pratt et al. (1997) from the area of the adjacent geological map sheet to the south. Here it consists of dacitic to rhyolitic pumice-lapilli tuffs and tuffites with quartz crystals and carbon fragments. According to Pratt et al. (op. cit.) it overlies the Turi Formation and appears to be post-dated by the Quimsacocha Formation.

4.11 Quimsacocha Formation (M_Q)

The Quimsacocha Formation crops out along the southern margin of the mapped area, in a belt approximately 4-5 km to the south and south-east of Soldados. It extends southwards into the area of the adjacent geological map, from where Pratt et al. (1997) named the formation after the eroded volcanic edifice of Quimsacocha.

The Quimsacocha Formation consists of a pile of andesite lavas and associated breccias which dip radially away from the rim of the Quimsacocha caldera. The rocks exposed within the mapped area represent the outermost northern flanks of the edifice. Here they are fresh, dark green-grey microporphyritic lavas and breccias, which contain microphenocrysts of plagioclase and abundant and distinctive acicular phenocrysts of amphibole which exhibit flow-alignment.

The formation rests with angular unconformity upon the Plancharumi and Jubones formations of the Saraguro Group. The precise age relationship with the Turi Formation within the mapped area is not clear. On topographical evidence it appears to rest upon the Turi Formation. Pratt et al. (op. cit.) also state that in the south and east the Quimsacocha Formation caps the Turi Formation. The formation appears to be draped by deeply weathered tuffs of the Tarqui Formation to the north-east, which is in accord with the observation of Pratt et al. (op. cit.) on the eastern flanks of the Quimsacocha edifice. The Turi Formation has yielded Late Miocene fission-track dates (Steinmann, 1997b) and the Tarqui Formation is equivalent to the Tambo Viejo Formation which has an uppermost Miocene age (6.3 ± 1.0 Ma) (Hungerbühler and Steinmann, 1996). If the contact relationships described above are correct, then the Quimsacocha Formation must be of Late Miocene age.

4.12 Tarqui Formation (M_{Tq})

The Tarqui Formation is preserved on the interfluves south-west of Cuenca, where it mantles the Turi and Quimsacocha formations.

It consists of highly weathered, poorly consolidated, white and red, kaolinized acid tuffs. A distinctive feature of these tuffs is the presence of abundant euhedral bipyramidal crystals of quartz, which weather out of the deposit and are concentrated in small residual pockets on the surface.

The tuffs of the formation are well-exposed in the road section between Sunsun [7154-96742] and [7086-96714]. Because of intense weathering it is difficult to recognise the original nature of the deposits. They include bedded and massive tuffs which contain the remnants of pumice lapilli. Based upon the examination of a limited number of exposures, it is concluded that the deposits probably include air-fall tuffs as well as pumice lapilli ash-flow tuffs. Near Sunsun there is also evidence of reworking with cross-cutting channels within the tuffs infilled with conglomerate.

Hungerbühler and Steinmann (1996) equated these youngest deposits in the Cuenca Basin with the Tambo Viejo Formation of the Nabón basin, which on the basis of zircon fission-track dates is assigned to the very latest Miocene (6.3 ± 1.0 Ma).

It has been suggested that the Quimsacocha caldera may have acted as a source for some of the Tarqui Formation tuffs (Pérez, 1990). Whilst this hypothesis cannot be refuted based on the presently available evidence, it appears to be unlikely on compositional grounds. The Tarqui tuffs appear to be very acid, whereas the rocks of the Quimsacocha volcanic edifice appear to be almost entirely andesitic, apart from a high-level intrusive stock of biotite dacite on the western rim of the caldera. Rhyolitic rocks are mapped within the Quimsacocha caldera, although at the time of the survey there was some debate as to whether these were in fact zones of silicification. Subsequent alteration studies based on drill cores support the notion that the silicic rocks of the caldera are silicified andesites. Therefore, in the absence at Quimsacocha of acid rocks (with distinctive bipyramidal quartz phenocrysts), it is considered unlikely that the tuffs of the Tarqui Formation were erupted from that volcanic centre.

4.13 Cisarán Formation (M_{Cn})

The Cisarán Formation crops out in the north-east of the area, from where it extends eastwards into the Cordillera Real and northwards into the area of the adjacent map.

The Formation is exposed along the Panamerican highway between Zhud and Tixán, and in the high ground to the east, from where it is named after the highest mountain of Cerro Cisarán (Plate 18). Here it has a thickness of about 2500 m and consists essentially of three subhorizontal units. These include a basal sequence of intermediate lavas, which are overlain by coarse volcaniclastic sedimentary rocks with intercalations of lava, which are in turn overlain by more intermediate lavas which cap all the high mountains of the area.

4.13.1 Stratigraphic relationships and age of the Cisarán Formation

The lavas in the lower part of the formation were originally mapped by Sosa and Longo as part of the Alausí Formation, which was presumed to be of Palaeogene age (DGGM, 1975). Later Kennerley (1980) correlated them with the Saraguro Formation (sic.) of assumed Oligocene age. Subsequently Egüez et al. (1992) assigned the rocks of the unit in the Alausí area and farther west to the Alausí Unit, of Miocene to possible Pliocene age.

The Cisarán Formation, as defined here, rests unconformably upon metamorphic schists and phyllites in the Guasuntos-Achupallas area. It also rests upon sheared sediments of the Yunguilla Unit and basalts of the Pallatanga Unit in the extreme north of the map area. Near Chunchi the formation rests unconformably upon folded volcanic rocks of the Puñay Unit, and farther south around Zhud and Juncal it rests upon the sediments of the Turi Formation. The nature of the contact between the Cisarán Formation and the underlying Turi Formation is uncertain. Steinmann (personal communication, 1997) believed that in the Juncal-Cañar area there is a change in inclination of bedding between the two units, implying the presence of an angular discordance. In terms of lithology however, the sediments of the two formations are similar.

In the north-east corner of the mapped area the Cisarán Formation is overlain by pumiceous lacustrine volcaniclastic sediments of the Quaternary Palmira Formation.

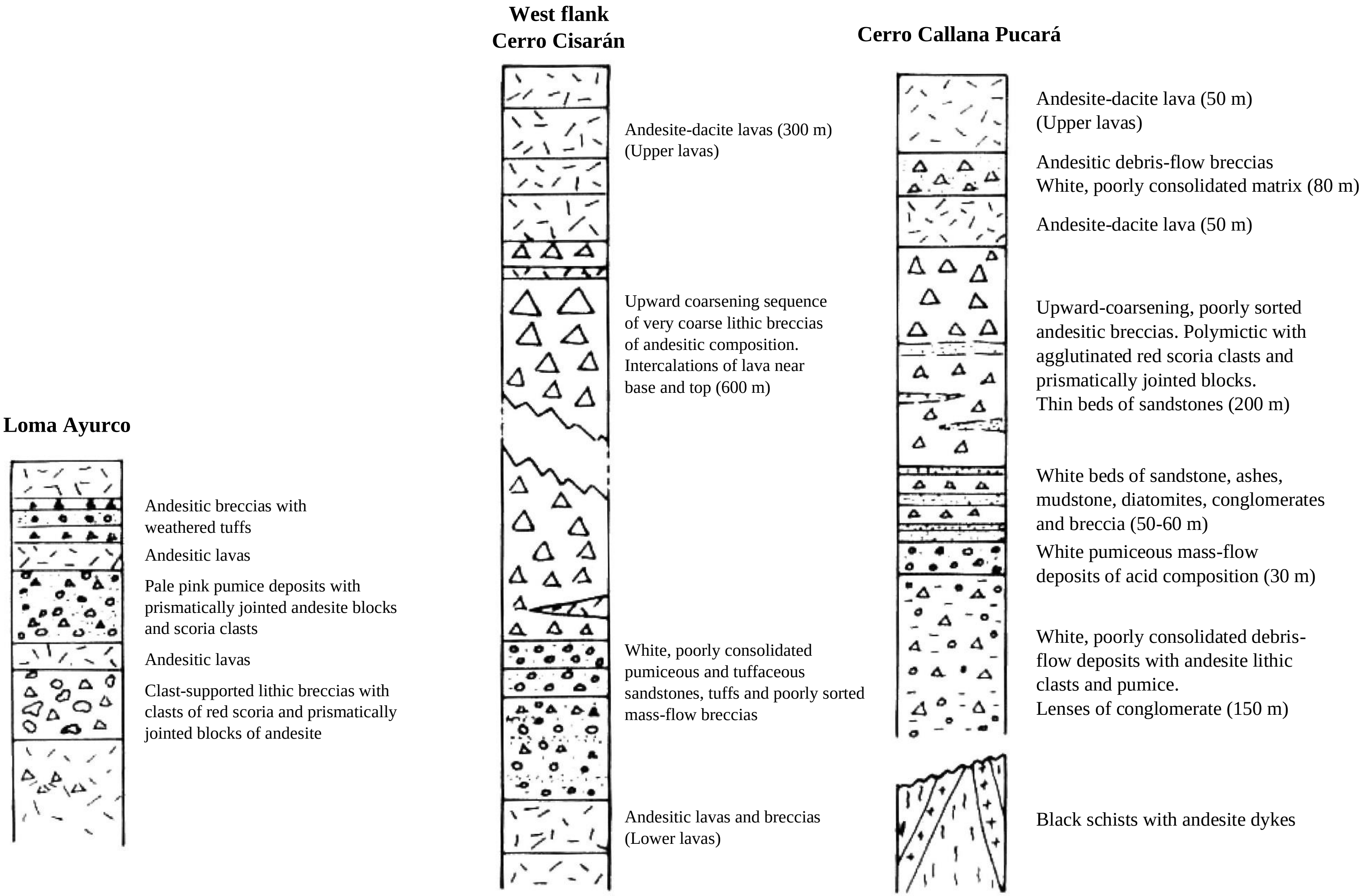


Figure 19. Sections through the Cisarán Formation (no vertical scale)

A fission-track age of 6.8 ± 0.8 Ma has been obtained from tuffaceous sediments low in the sequence between Zhud and Juncal (Steinmann, personal communication, 1997). Another fission-track age of 6.9 ± 0.7 Ma was obtained from lavas near the base of the formation in the extreme north of the area near Pallatanga. In addition, a K/Ar date of 7.15 ± 0.38 Ma has been obtained from a lava intercalated in the volcaniclastic rocks on the north-western flanks of Cerro Cisarán. These dates indicate a Late Miocene age for the formation.

On the published geological map, the rocks of the Cisarán Formation have been divided into three broad units. In the following description these are informally referred to as: Upper lavas, Volcaniclastic rocks and Lower lavas.

4.13.2 Lower lavas of the Cisarán Formation

The lowest exposed rocks of the formation are lavas and subordinate breccias of intermediate composition. These are well-exposed along the Panamerican highway between Compud and Alausí, and along the railway line to the north-east and south-west of Nariz del Diablo [7370-97525].

The lower lavas of the formation reach their thickest development of between 600-700 m in the area between Alausí and Chunchi [7315-9747]. They appear to wedge out in the area to the south-west of Compud Viejo [7295-97405], where the overlying volcaniclastic rocks of the formation rest directly upon sediments of the Turi Formation with no intervening lavas.

The rocks exposed along the highway consists mainly of pale to dark grey coloured microporphyritic lavas with lesser amounts of breccia. The lavas have tabular and lenticular cross-sectional forms. They are fine grained to almost glassy and contain microphenocrysts of plagioclase, amphibole and clinopyroxene, although some are devoid of amphibole and contain microphenocrysts of pleochroic orthopyroxene (hypersthene). No analyses have been obtained from these lavas, but by analogy with similar lavas from the top of the formation which have been analysed (Table 10), they are assumed to be of high-silica andesite and basic dacite composition.

A section was also examined along a traverse extending from the Panamerican highway via the settlement of Tolte [7361-97514] to the railway station at Nariz del Diablo [7362-97522], and from there south-westwards along the railway line to the station at Chanchán. Between Tolte and Nariz del Diablo there are a few outcrops of grey andesitic lava. In the bottom of the valley around the station of Nariz del Diablo, pale grey-green and khaki weathered hornblende andesite lavas and breccias are exposed. The breccias are only apparent on close examination and are composed of angular to subangular clasts of andesitic lava with diffuse margins set in a matrix of similar appearance. These are interpreted as autoclastic breccias although some may represent the products of block-and-ash pyroclastic flows. Passing south-westwards along the railway line, hornblende andesites and breccias are exposed. The andesites in this part of the section appear to be intrusive stocks and sheets rather than lavas.

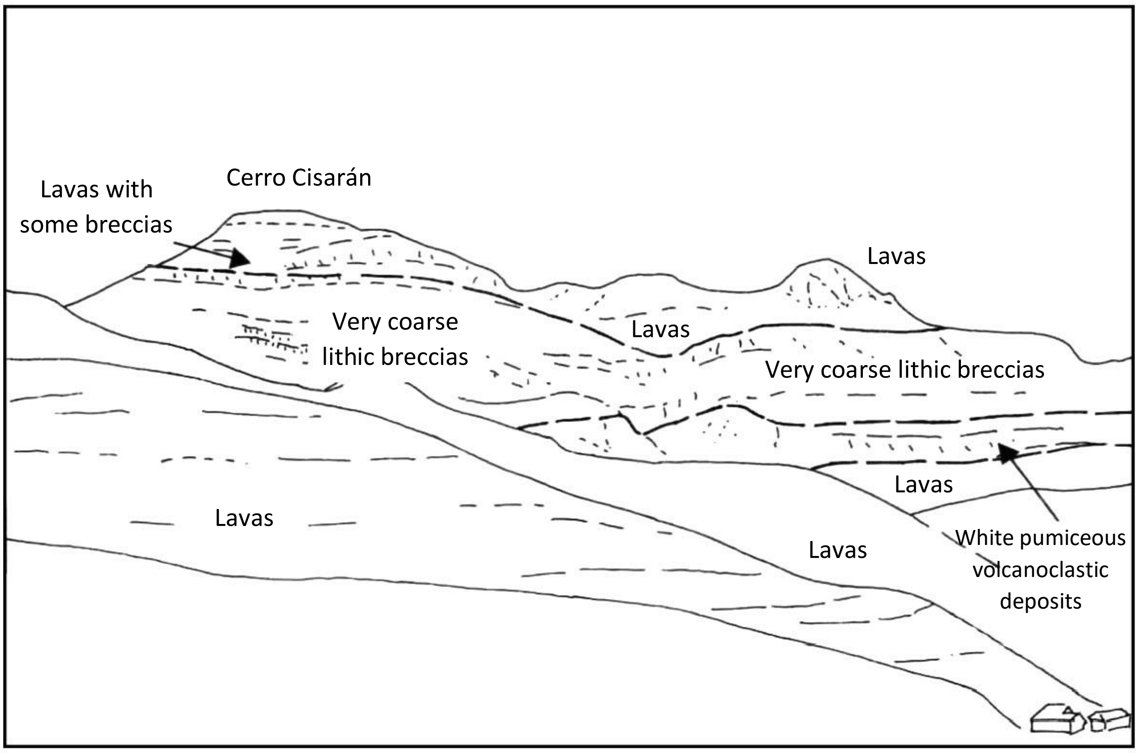


Plate 18. Cerro Cisarán viewed from the Panamerican highway near Alausí looking south. The mountain is composed mainly of horizontally stratified volcanoclastic rocks which are capped by lavas of andesitic to dacitic composition

The remnants of a rhyolite dome occur at Loma Llallarán [7406-97585], which is situated a short distance to the north of Alausí. Sections on the western side of the hill (above the railway line) indicate that the rhyolite body cross-cuts the andesite lavas of the formation and has hydrothermally altered them. The summit of the hill has the form of a dome, the eastern flank of which is cut by the Panamerican highway which exposes intensely flow-banded, flow-folded and autobrecciated rhyolites [7413-97585]. The breccias are typical of autobreccias that develop on the flanks of rhyolite domes, and are taken as evidence that at this structural level the dome was extrusive. The dome is therefore considered to have been partly intrusive and partly extrusive within the Cisarán Formation.

Andesitic lavas also occur in the lower part of the formation near the northern margin of the map. A zircon fission-track date of 6.9 ± 0.7 Ma was obtained from a sample (M3-946) taken from a lava near the base of the formation at [7309-97776].

4.13.3 Volcaniclastic rocks of the Cisarán Formation

The lower lavas of the formation are overlain by volcaniclastic rocks, which in the Chunchi-Cerro Cisarán area have a maximum thickness of about 1500m. These consist predominantly of very coarse, poorly sorted intermediate breccias, but also include tuffaceous sandstones and siltstones and re-worked tuffs and primary pyroclastic rocks. Lavas are also intercalated within the uppermost volcaniclastic rocks.

In several areas a transitional zone occurs between the volcaniclastic rocks and the underlying lower lavas. In this transitional zone primary pyroclastic rocks and lavas are intercalated with reworked volcaniclastic rocks. This is exemplified by a 200 m thick section exposed in the basal part of the volcaniclastic unit at Loma Ayurco [7365-97555], situated about 3 km west of Alausí. The section consists of hornblende andesite lavas and breccias, and massive, poorly lithified, cream and pale pink coloured pumice lapilli tuffs and pumice lapillistones. These pumiceous rocks are interpreted as the products of pumice-flows and ash-flows (*ignimbrites*). Some of the breccias are autoclastic, although others are polymictic and are probably of epiclastic origin. Several massive breccia units also contain reddened scoria clasts and prismatically jointed blocks of andesite, indicating that they were hot when emplaced and possibly included juvenile magmatic material. These breccias are probably the products of block-and-ash flows (*nuées ardentes*).

The most complete sections through the volcaniclastic rocks are exposed in the escarpment to the east of the Panamerican Highway, where the horizontally stratified strata make up the flat-topped mountains of Cerro Callana Pucurá [7460-97455] and Cerro Cisarán [7439-97432]. Here they rest upon metamorphic schists, which on the road between La Moya [7438-97528] and Achupallas [7484-97478] are intruded by numerous dykes, inclined sheets and stocks of andesite which are interpreted to have been feeders to the lavas of the Cisarán Formation.

Plate 19. Creamy white tuffaceous and pumiceous volcanoclastic sediments of the Cisarán Formation in the lower part of the western flank of Cerro Cisarán

Plate 20. Very coarse poorly sorted breccias and breccio-conglomerates near the summit of Cerro Cisarán, looking west. Note the figures on the outcrop for scale

An instructive section occurs on the eastern flank of Cerro Callana Pucurá, between the Escuela Nudo del Azuay [7476-97472] and the summit of the mountain (Figure 19). This section consists of approximately 600 m of horizontally stratified, cream-coloured tuffaceous sediments and coarse breccias, with several lavas near the top. Notably, no clasts of the underlying schists have been recognised in these coarse clastic sediments. The lowest rocks near the school consist of approximately 150 m of poorly exposed, white to cream-coloured, mass-flow breccias composed of andesitic lithic clasts and pumice lapilli supported in a tuffaceous matrix. Thin stringers and lenses of mature conglomerate occur within these deposits. Approximately 30m, of massive, poorly lithified, white-weathering pumice lapilli tuff outcrops near the aqueduct at [7471-97472]. This is composed mainly of dacitic tubular pumice lapilli (making up 60% of the rock) and minor lithic clasts, supported in a deeply weathered white tuffaceous matrix. It is interpreted as the product of a pumice-flow (*ignimbrite*) which was probably deposited subaqueously. This pumiceous unit is overlain by 50-60 m of stratified, poorly cemented, cream-coloured tuffaceous clays, silts, diatomites, sandstones and mature conglomerates, with intercalations of andesitic breccia and breccio-conglomerate of debris-flow origin. These cream-coloured sediments are overlain in the main part of the escarpment by 200 m of crudely stratified andesitic breccias with thin intercalations of cross-bedded and planar bedded volcanic sandstone. The breccias that coarsen upwards and towards the top of the sequence contain andesite blocks more than a metre in diameter. In the lower half of the escarpment, around [7467-97459], the breccias are strongly indurated and contain reddened agglutinated andesitic scoria clasts and radially and prismatically jointed blocks of andesite with reddened carapaces. These features indicate that the clasts were probably hot when emplaced, and the breccias are interpreted as the products of hot avalanches or block-and-ash pyroclastic flows. At the top of the main escarpment the breccias are overlain by a laterally extensive andesite lava approximately 50 m thick which forms a prominent bench-like feature. This is in turn overlain by about 50 m of poorly exposed creamy white matrix-supported debris-flow breccias, which are capped at the top of the mountain by another lava which is approximately 80 m thick.

A similar volcaniclastic sequence is exposed in the escarpment on the western flank of Cerro Cisarán. Here white to buff-coloured, horizontally stratified sediments are exposed in cliffs at the base of the escarpment around Loma Ulumpala [7434-97455]. These were not examined, but are assumed to be the same as the white tuffaceous and pumiceous sediments, tuffs and breccias described from the east side of Cerro Callana Pucará (in the previous paragraph). They are overlain in the main part of the escarpment by about 600 m of very poorly sorted, upward-coarsening polymictic andesitic to dacitic lithic breccias, which towards the top of the escarpment contain clasts exceeding 5 m in size (Plate 20). Several lavas are intercalated within the breccias at the top of the escarpment and also form a cap to the sequence. Analysis indicates these are of transitional high-silica andesite to very basic dacite composition. A sample (PND-1083) collected from the lowest lava flow at [7429-97441] has yielded a hornblende K/Ar radiometric age of 7.15 ± 0.38 Ma.

To the south of Cerro Cisarán, similar volcaniclastic rocks and lavas make up the escarpments in the area to the east of the Panamerican Highway as far south as Zhud [7220-97282] and Juncal [7265-97257]. As at Cerro Cisarán, the sequence commences with weathered, poorly lithified, cream-coloured, matrix-supported tuffaceous mass-flow breccias, tuffaceous sandstones, siltstones and reworked tuffs. Steinmann (personal communication, 1997) obtained a zircon fission-track age of 6.8 ± 0.8 Ma from fine tuffs near the base of the sequence [7232-97252]. These pale-coloured tuffaceous rock pass up into a coarsening upwards sequence of poorly stratified, poorly sorted, coarse andesitic lithic breccias and breccio-conglomerates which are generally grey in colour. Good sections can be seen through these rocks in the Río Guallicanga-Loma Huahua Carshao area [7275-97290], although the most spectacular coarse breccias are exposed in the escarpment between Compud Viejo [7295-97405] and the summit of Cerro Pumamaqui [7322-97352], where they reach a thickness of about 1100 m and give rise to a distinctive pillared topography.

To the north of the Cerro Cisarán area, the same broad sequence of volcaniclastic rocks is exposed in the escarpments surrounding the plateau of Pachamama [7447-97566]. Here they rest upon the lower lavas of the formation and upon basement schists. As in the other sections, they commence with cream to buff-coloured tuffaceous sandstones, siltstones and mass-flow breccias, which pass up into coarse, dark grey andesitic lithic breccias with lavas intercalated near the top. Between Guasuntos [7435-97535] and the summit of Pachamama the volcaniclastic sequence has a thickness of about 800 m. Passing northwards towards Tixán [7446-97624] the sequence is poorly exposed but appears to thin rapidly.

The rocks of the formation have been examined in a number of sections in the area extending from Sibambe [7347-97543] to the northern margin of the map. Throughout this large expanse of ground, the Formation consists mainly of a monotonous sequence of andesitic debris-flow lithic breccias and subordinate volcanic sandstones. Andesitic lavas are also intercalated within these clastic rocks in some areas, as for example in the escarpment immediately to the east of Chacallo [7390-97705] and in the road section between Moraspamba [7368-97620] and Pampa [7335-97669]. Within this northern sector the formation has been faulted and tilted, and the strata dip at angles of up to 70 degrees.

4.13.4 Upper lavas of the Cisarán Formation

Lavas are intercalated within the uppermost volcaniclastic rocks and also overlie them forming a capping to almost all the flat-topped mountains to the east of the Panamerican Highway.

The original thickness of the upper lavas is unknown because of erosion. They form an extensive cap to the plateau of Pachamama to the east of Alausí, where they are estimated to have a thickness of about 150 m. On the summit of Cerro Cisarán four massive lavas have a total thickness of about 300m.

The most extensive upper lavas occur in the páramo to the south-east of Cerro Cisarán, in the general area between Cerro Coronado [7335-97364], Cerro Estero [7322-97318] and Cerro Carshao [7282-97305], where they have a thickness of about 300 m. They have been mapped as far south-east as Laguna Culebrillas [7385-97325], but extend farther to the east into the Cordillera Real.

Table 10. Chemical analyses of lavas from the top of the Cisarán Formation

Sample	PND-339	PND-1047	PND-1079	PND-1081
SiO_2	62.95	63.20	63.31	62.32
TiO_2	0.74	0.72	0.69	0.73
Al_2O_3	17.44	17.26	17.34	17.52
Fe_2O_3	4.90	5.14	4.94	4.86
MnO	0.06	0.07	0.07	0.07
MgO	2.04	2.32	2.13	2.06
CaO	5.48	5.43	5.29	5.92
Na_2O	4.19	3.94	4.13	4.48
K_2O	1.25	1.41	1.32	1.41
P_2O_5	0.26	0.23	0.21	0.29
LOI	0.18	0.30	0.15	0.16
TOTAL	**99.49**	**100.02**	**99.58**	**99.82**
Ba	568	745	630	670
Ce	39	27	19	38
Co	15	12	18	16
Cr	26	32	25	28
Cs	0	0	1	0
Hf	6	4	4	0
La	14	20	11	8
Nb	6	4	5	6
Nd	25	21	16	24
Ni	12	17	15	18
Rb	14	27	23	16
Sc	13	13	14	10
Sm	3	11	10	10
Sr	996	884	755	1212
Ta	0	0	0	0
Th	2	2	1	2
U	2	3	3	0
V	141	140	133	137
Y	9	17	8	7
Zr	108	111	109	117

Petrographically the upper lavas are similar to the lower lavas at the base of the formation. They are fine-grained aphyric and microporphyritic rocks, containing microphenocrysts of plagioclase and varying amounts of amphibole or pseudomorphs of oxide after amphibole. The groundmass varies from being glassy to cryptocrystalline with strong pilotaxitic textures produced by the flow-alignment of feldspar laths and microlites. The chemical analyses of four lavas presented in Table 10 indicate transitional high-silica andesite to basic dacite compositions.

4.13.5 Summary and discussion of the Cisarán Formation

The Cisarán Formation outcrops in the north-east of the area and consists of up to 2500 m of intermediate lavas and coarse-grained volcaniclastic rocks of Late Miocene age.

The Formation rests unconformably upon basement schists, the Pallatanga Unit, the Yunguilla Unit and the Saraguro Group. It also rests upon the Turi Formation, although the nature of the contact is uncertain but may be discordant. The formation is in turn overlain by the Quaternary Palmira Formation.

Three informal lithological units have been mapped. The oldest part of the formation consists of andesitic to basic dacite lavas and breccias, which reach a thickness of 600 to 700 m in the Alausí-Chunchi area. These are overlain by coarse volcaniclastic rocks up to 1500 m thick, which consist mainly of very coarse breccias but also include pumiceous pyroclastic rocks and intercalations of lava. The upper part of the formation is represented by andesitic and basic dacitic lavas up to 300 m thick.

The volcaniclastic rocks in the middle part of the formation are mainly epiclastic and generally coarsen upwards. The lowest of these are cream-coloured tuffaceous rocks, which include reworked tuffs, tuffaceous sandstones, siltstones, diatomites and pumiceous mass-flow breccias, as well as primary pumice lapilli ash-flow tuffs. Some of these rocks were deposited in standing water, and the abundance of pumiceous and tuffaceous material indicates explosive activity of a fairly siliceous nature within the source area. Local volcanism within the depositional environment is manifested by intercalations of lava and by the presence of block-and-ash pyroclastic flow breccias, which were probably formed on the flanks lava domes. The sediments pass up into very coarse to extremely coarse very poorly sorted lithic breccias and breccio-conglomerates of andesitic to dacitic composition.

The pale coloured volcaniclastic and pyroclastic rocks in the lower part of the sequence are believed to have been deposited in a fluvio-lacustrine environment. The overlying upward-coarsening lithic breccias are interpreted as the products of prograding alluvial fans derived from a source area composed of intermediate lavas.

4.14 Quaternary deposits

Alluvium (Q_A) is present in all the river valleys and forms very extensive expanses along the margins of the cordillera in the coastal plain and in the Cuenca Basin. Large alluvial fans (Q_{Ca}) exist where the main rivers disgorge onto the coastal plain and colluvial fans (Q_C) occur in the mountainous areas prone to landslips. Alluvial terraces occur in some of the larger valleys, as for example in the Chimbo Valley south of Pallatanga.

Quaternary volcanic deposits (Q_V) mainly consist of fine air-fall ashes (cangagua) which mantle large areas in the north-east, extending as far south as the Huigra area. Unconsolidated dacitic or rhyolitic pumice flow deposits (ignimbrites) are also preserved on the valley sides near Alausí. These massive pumiceous deposits are at least 10 m thick and are exposed in a number of roadside cuttings, as for example at [7390-97575] on the road between Alausí and Sibambe. They undoubtedly originate from one of the major Quaternary volcanic centres in the Riobamba area to the north. Examination of satellite images suggests that they may represent the southernmost limit of an ignimbritic sheet originating from Igualata.

Relatively thick fluvio-lacustrine volcanic sediments (Q_{Vs}) occur in the north-east of the area on either side of the Panamerican Highway between Tixán and Palmira. These were previously mapped as the Palmira Formation (DGGM, 1975) and consist of poorly consolidated pumiceous deposits, tuffs, sandstones and diatomites.

Young lacustrine deposits (Q_L) including sands, conglomerates and fine tuffs occur near Chanchán where the valley appears to have previously been dammed by a large colluvial fan.

5. INTRUSIVE ROCKS

The intrusive rocks of the area have only been mapped in a cursory manner and very few have been examined petrographically. The following description is therefore based upon the general distribution and macroscopic features of the intrusions.

The intrusions of the area consist mainly of plutonic granitoids and diorites. These show a crude distribution pattern, in which granitoid intrusions occur in the lowest ground along the western foothills, whereas diorites mainly occur in a zone at higher altitudes to the east of the granitoids. Minor gabbro and microgabbro bodies are found within the Pallatanga and Macuchi units. High-level subvolcanic rhyolites, microdiorite sills and andesite dykes intrude the Saraguro Group.

5.1 Granodioritic intrusions

The largest intrusion outcrops over several hundred square kilometres in the south-west of the area. This has informally been referred to as the Chaucha batholith. It intrudes metamorphic rocks, the Pallatanga Unit, Yunguilla Unit, Angamarca Group and the Saraguro Group.

The main outcrop occurs in the foothills to the south-east of Naranjal, although numerous smaller bodies intrude the basalts of the Pallatanga Unit as far south as the Ponce Enríquez area of the adjacent geological map. Throughout this ground the basalts are hornfelsed, suggesting that they may be underlain by the batholith at a shallow depth, and that the granitoid bodies outcropping within the basalts are apophyses. Such a conclusion is supported by geological mapping and visual observations, which indicate that the roof zone of the batholith is generally flat-lying. This is apparent for example in the Chaucha area, where a relatively flat-lying contact between the intrusion and overlying country rocks can be recognised over a large area by changes in soil colour, with soils derived from the intrusion being pale to almost white.

The batholith is composed of several different intrusive phases. The bulk of the intrusion has been broadly classified in the field as a biotite hornblende granodiorite, but where the intrusion has been studied in detail at Chaucha the main rock type has been identified as a tonalite (Misión Belga, 1986). In general the intrusion consists of a medium-grained, equigranular, leucocratic rock composed of plagioclase, biotite, hornblende and accessory quartz and K-feldspar. Biotite tends to be more abundant than hornblende.

The main granodiorite-tonalite intrusion is intruded in several areas by diorites. These can be seen for example on the road approaching Carmen de Pijilí and on the Cascajo Ridge above Chaucha. The diorites are medium- to fine-grained, equigranular, mid grey-green rocks composed mainly of plagioclase feldspar and chloritised amphibole with only traces of quartz. Mineral exploration within the Chaucha area has also identified a number of younger stocks of “quartz diorite” or “dacite porphyry” which intrude the tonalite and are thought to be related to the porphyry mineralisation.

Two K/Ar ages of 9.77 ± 0.29 Ma (Müller-Kahle and Damon, 1970) and 12 ± 0.6 Ma (Snelling, 1969) are reported from Chaucha. In view of the extensive hydrothermal alteration of the Chaucha area, these dates are probably related to the intrusion of diorites into the main tonalite-granodiorite, which are believed to have caused the mineralisation (López et al., 1983). The age of intrusion of the main granodiorite-tonalite body is therefore possibly older.

Farther north, a large linear body of granodiorite is intruded along the belt of metamorphic rocks and also along the contact between these and the basalts of the Pallatanga Unit. A smaller linear body of granodiorite also intrudes the contact between the Angamarca Group and the Pallatanga Unit along the Río Yanayacu [6970-97330].

These linear intrusions are composed of biotite-hornblende granodiorite of very similar appearance to the granodiorite-tonalite of the Chaucha batholith. The larger of these two linear intrusions is well-exposed in the lower reaches of the Río Patul and along the old road between Cochancay and Javín. For the most part of the intrusion is a medium- to coarse-grained equigranular rock, although close to the margin it is sheared and weakly foliated.

5.2 Diorites intrusions

The largest diorite intrusion outcrops over an area well in excess of 100 km^2 around San Felipe de Molleturo and northwards as far as the Río Patul. It is well-exposed along the main road between Miguir and San Felipe, and on the old road between San Felipe and Corona de Oro. For reference purposes this intrusion is informally referred to in this report as the Molleturo diorite. It is a medium- to coarse-grained leucocratic hornblende diorite with little or no quartz. Although more detailed mapping is required to ascertain the precise extent and shape of the outcrop, the intrusion does appear to cross-cut the major NE-SW shears which form the boundaries between the metamorphic rocks, the Pallatanga Unit and Yunguilla Unit without obvious displacement.

A small body of coarse-grained quartz monzonite (or possibly quartz syenite) with prominent pink phenocrysts of K-feldspar occurs at the margins of the Molleturo diorite at [6870-96920].

Smaller stocks and sill-like intrusions of hornblende diorite occur in the north of the area. One such diorite at [7189-97429] has yielded a K/Ar age of 7.59 ± 0.35 Ma. This could be an intrusion related to the Late Miocene andesitic-dacitic volcanism of the Cisarán Formation. A similar high-level stock of porphyritic hornblende diorite (andesite) intrudes the Cisarán Formation at Loma Chiripungu [7380-97550] near Alausí and has yielded a K/Ar date of 7.9 ± 0.4 Ma as well as an older date of 12.5 ± 0.9 Ma (Egüez et al., 1992). The younger of the two dates is preferred by Lavenu et al. (1992), and this conclusion is also supported by evidence from the present study which shows that the Cisarán Formation country rocks are significantly younger than the older date.

5.3 Andesite dykes and meladiorite sills in the Saraguro Group

A swarm of andesite dykes intrudes the Chanlud Formation and the older units of the Saraguro Group within the Cajas area. These acted as feeders to the andesitic lavas of the Chanlud Formation. As described in section 4.7.6.8, the dykes mainly trend NW-SE although a crudely radial pattern is developed around Patul where there may have been a volcanic centre. They are believed to have developed in a tensional pull-apart regime (Section 4.7.6.9, 6.1.2 and 8).

Rare occurrences of NW-SE trending andesite dykes also intrude the Río Blanco Formation.

Discordant sills and irregular apophyses and sheets of meladiorite intrude the Chanlud Formation and Río Blanco Formation. Those within the Río Blanco Formation are fine-grained, whereas those intruding the Chanlud Formation tend to be medium-grained. They are interpreted as high-level sub-volcanic intrusions that were broadly comagmatic with their andesitic host formations. Evidence for this interpretation is seen in the Chanlud Formation, where the diorite bodies are intruded by andesite dykes. Since the dykes acted as feeders to the lavas of the formation, the diorite sheets must have been broadly coeval with the formation as well.

5.4 Rhyolite intrusions

High-level rhyolite domes and sills intrude the Saraguro Group in a number of areas.

Several intrusive-extrusive rhyolite domes occur within the Chulo Unit around Laguna Totoras [6976-96930]. These intrusions show classic domal forms with flow banding, flow-folding and breccia carapaces.

Another group of rhyolite domes occurs in the Cañar Valley. These intrude the tuffs of the Tomebamba Unit. The largest intrusion occurs at Ger [7185-97235], which is composed of three or four coalesced domes which outcrop on either side of the Río Cañar. The eroded top of one of these domes is thought to be overlain by Late Miocene sediments of the Turi Formation at [7195-97253]. Another steep-sided rhyolite dome or plug belonging to this group occurs to the north-west near Achupallas. The mineralised top of this rhyolite is exposed in a roadside quarry at [7135-97269]. The age of this group of domes is uncertain. They appear to pre-date the Turi sediments and probably belong to the Saraguro Group. It is possible that they were coeval with the voluminous rhyolitic ash-flow tuffs of the Cerro Caucay Formation which outcrop a short distance to the east.

The largest rhyolite intrusion occurs to the east of Chulo and Patul. It intrudes the Chulo Unit and the Chanlud Formation. The main body of this intrusion appears to be broadly domal, although the northern offshoot is undoubtedly sill-like. It has prominent columnar joints and is flow-banded and flow-folded. Contact relationships indicate that this intrusion post-dates the Chanlud Formation. It may have been coeval with the rhyolitic volcanism of the Cerro Caucay Formation.

6. STRUCTURE

6.1 Faults and fracture traces

Faults dominate the structure of the area. The regional trend is predominantly NE-SW to NNE-SSW, although in the south of the area NW-SE and to a lesser extent E-W trends are important.

6.1.1 NE-SW to NNE-SSW trending faults

The largest and most important faults occur in a NE-SW trending zone of parallel and anastomosing fractures which extends along the western margin of the area. The faults within this zone mainly strike NE-SW, although in the north of the area they curve into a NNE-SSW to almost N-S trend.

The main faults within this zone mark the boundaries between several fundamental and contrasting lithotectonic units (Figure 22). The most north-westerly of these major faults is the **Chimbo-Cañi Fault** which runs along the Chimbo Valley and extends northwards into the Pallatanga area. This consists of a continuous fault along the Chimbo Valley, and a number of splays which link with the Multitud Fault to the south-east. The principal fracture of the Chimbo-Cañi Fault system acts as the contact between Palaeocene-Eocene island arc rocks of the Macuchi Unit to the north-west, and similar aged turbiditic sedimentary rocks of the Angamarca Group to the south-east.

The **Multitud Fault** runs parallel with the Chimbo-Cañi Fault to the south-east, and is interconnected with it by a number of splay faults. It cuts across the grain of the topography and forms the boundary between the Angamarca Group to the north-west and Cretaceous ocean floor basalts of the Pallatanga Unit to the south-east.

The **Bulubulu Fault** is the most south-easterly of the three main NE-SW trending faults. It is named after the prominent valley of the Río Bulubulu and marks the contact between oceanic basalts of the Pallatanga Unit on the north-west side, and metamorphic rocks which form a basement to the younger volcanic cover of the cordillera to the south-east. The Bulubulu and Multitud faults converge northwards and merge to form the **Pallatanga Fault System** of the adjacent map area to the north (McCourt et al., 1997, BGS-CODIGEM, 1998a).

Both the Pallatanga and Chimbo-Cañi fault systems represent major lithotectonic terrane boundaries or sutures which can be traced northwards and southwards along the length of the Western Cordillera (Figure 22). The rocks within and adjacent to these fault zones are strongly sheared. This can be seen for example in the strongly sheared and mylonitic basalts of the Pallatanga Unit along the main road west of Molleturo (Section 4.3.4), and in the schists adjacent to the basalts at La Delicia [6940-97257]. The sediments of the Angamarca Group are also strongly sheared where they are in contact with the Macuchi Unit along the Chimbo-Cañi fault, as can be seen for example in the Río Piedritas [6858-97385].

Displaced outcrop patterns of the Macuchi Unit and Angamarca Group in the area between La Troncal and Cumandá suggest dextral strike-slip movement along these major faults. Limited evidence from S-C mylonitic structures also indicates dextral shear. More detailed structural analysis of these shear zones in the cordillera farther north, particularly in the sector between the Equator and 1°S (Hughes and Bermúdez, 1997), provides additional evidence for dextral strike-slip movement. Winter and Lavenu (1989) also showed that the main fracture of the Pallatanga Fault is part of a system of parallel dextral strike-slip faults. The total displacement along the Pallatanga Fault was estimated to have been 9 km, with about 60 m of this having occurred during the Holocene, as inferred from neotectonic structures and the displacement of geomorphological features. Megard et al. (1986) on the other hand report that in the Pallatanga area the modern fault plane of the Pallatanga Fault dips to the east at 50° and that the rocks to the east override those to the west (i.e. a reverse fault). This however implies a single fault plane, whereas the present study shows the structure to be more complex.

Several other NE-SW trending faults occur within the area. The most prominent of these is the Chaucha-Río Jérez lineament which runs along the Río Jérez and passes south-westwards through Chaucha into the area of the adjacent map. The sense of movement or displacement is unknown, but the lineament is very clear on aerial photographs and satellite images. It appears to control the position of a faulted inlier of metamorphic rocks in the Chaucha area, and it may also have accommodated collapse or subsidence in the Laguna Yanacocha area during the eruption of the ignimbritic tuffs of the Soldados Formation (Section 4.7.8.5). The lineament may extend northwards into the Filo Cajas-Patul area, where a number of smaller NE-SW faults occur within the volcanic cover rocks.

Another NE-SW trending fault occurs in the extreme south-east corner of the map, where it juxtaposes sediments of the Ayancay Group against volcanic rocks of the Saraguro Group. This represents the northern end of the Girón Fault System, which extends south-westwards across the entire geological map area to the south (BGS-CODIGEM, 1998c). Pratt et al. (1997) describe this fault system as a complex zone of faulting, thrusting and folding which controlled deposition and erosion during Saraguro Group times, and also controlled intermontane basin sedimentation in the Miocene.

6.1.2 NW-SE trending faults, lineaments and dykes

In the high ground to the west and north-west of Cuenca, the rocks of the Saraguro Group are fractured by NW-SE trending faults. These lineaments are evident on aerial photographs and satellite images, and are often represented by topographic features on the ground. However, displacement or sense of movement along these fractures is virtually impossible to prove at the scale of mapping due to the massive and poorly stratified nature of the volcanic rocks.

This fracture trend may be a relatively superficial feature, representing Reidel shears formed in the cover in response to strike-slip movements along the fundamental NE-trending shears, such as the Bulubulu, Multitud and Chimbo-Cañi faults to the north-west and the Girón Fault System to the south-east.

A swarm of NW-SE trending andesite dykes also occurs in this high ground. These acted as feeders to the voluminous lavas of the Chanlud Formation. The dykes indicate NW-SE tension during the eruption of the Chanlud Formation in the Early Oligocene. As suggested in Section 4.7.6.9, this may have developed in a pull-apart structural regime as a result of strike-slip movement on the NE-SW trending regional shears, such as the Bulubulu and Chimbo-Cañi faults.

6.1.3 E-W trending fractures

A number of E-W trending lineaments have been recognised on aerial photographs in the south of the area. No sense of movement or displacement has been proven on these lineaments.

A strong E-W trending fracture, which is almost certainly a fault, is apparent on aerial photographs a short distance to the north of the Río Blanco prospect. A second much larger parallel lineament occurs a short distance farther to the north. This runs along the Quebrada Paredones in the west and extends as far east as the Filo Cajas, passing a short distance to the south of San Felipe de Molleturo. Highly sheared rocks of the Río Blanco Formation are exposed where the trace of this fracture crosses the main road near San Felipe de Molleturo. At the eastern end the fracture trace bifurcates into a series of splays in the headwaters of the Río Miguir. These splays coincide with the development of E-W trending quartz veinlets in the Filo Cajas area [6915-96950] (Section 7.2.11).

6.2 Folds

Folds have only been recognised within a few areas, and where they do occur, they mainly have NE-SW to NNE-SSW trending axes.

For the purpose of description, the folds of the area are described under two headings. These are folds within the Saraguro Group and younger strata to the south-east of the Bulubulu Fault, and folds within the Angamarca Group to the north-west of the fault.

6.2.1 Folds to the south-east of the Bulubulu Fault

The rocks of the Saraguro Group record an episode of folding and erosion during the uppermost Eocene or basal Oligocene. Evidence for this is provided by the fact that the Chulo Unit and Filo Cajas Unit generally dip at moderate angles (up to 60°) towards the NW and are unconformably overlain by the Tomebamba Unit and younger volcanic units of the group which are subhorizontal or dip gently (<20°) towards the east and south. Within the Chulo Unit two-fold closures have been recognised. These include a broad open NE-SW trending syncline centred on Cerro Arquitecto [6943-96928] and an open concentric NE-SW trending anticline in the Quebrada de Niplay [6835-96898].

Folding is also seen within the Puñay Unit. In the massive andesitic lavas, breccias and sandstones of the upper parts of the unit this is manifested by a broad, open syncline with a NE-SW trending axis passing through El Tocte [7180-97385]. Less competent siltstones and sandstones lower in the Unit are more tightly folded, and locally beds are vertically inclined, as can be seen for example in the railway line section between Huigra and Chanchán, and in the road between Javín and San Antonio de Gualleturo.

The inclination of strata seen throughout much of the Saraguro Group in the high ground to the west and north-west of Cuenca is probably caused by faulting and tilting of fault blocks. Similarly, the sediments of the Turi Formation on the north side of the Río Cañar between Suscal and Zhud show variations in inclination due to faulting and the tilting of fault blocks.

The inclination of the strata of the Cerro Caucay Formation deserves special mention. These massive rhyolitic ash-flow tuffs form a subhorizontal sheet in the high-páramo west of Cañar, but along the south side of the Cañar Valley there is an abrupt change in attitude of the strata, which dip at 40°-45° north-eastwards into the valley. This suggests a monoclinal structure with a NW-SE trending flexure (or axis) running parallel to, and slightly to the south of the Río Cañar.

6.2.2 Folds to the north-west of the Bulubulu Fault

The sediments of the Angamarca Group generally dip and young towards the south-east, although locally beds are vertical or dip to the north-west. Where folds are seen, they have tight closures, amplitudes of 10's of metres and have upright axial planes trending NE-SW.

The Macuchi Unit has not been examined in detail and no fold closures have been recognised, although the strata strike NE-SW and either dip steeply towards the SE or NE suggesting the presence of NE-SW trending folds.

7. ECONOMIC GEOLOGY

7.1 Introduction

This section provides a brief listing and summary of the prospects and known mineralised zones within the mapped area.

One of the main problems in trying to compile a systematic description of the mineralisation of the region is that there is a scarcity of available written information on many of the prospects, even in official archives.

The following descriptions are based partly upon archival material where available, and partly on information collected during the geological survey. Given the reconnaissance nature of the mapping project, large areas remain unexplored. The description and listing of mineralisation are therefore far from complete. One of the objectives of this section is therefore to describe the salient features of the known mineralisation and where possible place this in the context of the new geological framework which has arisen from the mapping project. The prospects and areas of known mineralisation are described in approximate order from south to north.

The stream sediment geochemical exploration survey undertaken as part of the present project has also produced a great deal of new and valuable information relating to mineralisation within the area. These data are described by Williams et al. (1998), although some of the anomalies are also mentioned in the descriptions that follow.

7.2 Mineralisation

7.2.1 Gold mineralisation at Carmen de Pijilí

Carmen de Pijilí [6646-96725] has been the most important centre for artisanal gold mining within the area of the map. Virtually no descriptions of the mineralisation exist, except that the Au is reported to occur in polymetallic quartz veins.

Numerous small gold workings exist, and at the time of the survey there appeared to be an expansion in activity. The most significant working is an abandoned mine at [6620-96722]. This and several other workings in the area occur within hornfelsed basalts of the Pallatanga Unit and sediments presumed to belong to the Yunguilla Unit, close to the contact with diorite and granodiorite intrusions of the Chaucha batholith.

7.2.2 Chaucha Cu-Mo porphyry system

The most well-known mineral prospect within the mapped area is the porphyry copper-molybdenum deposit at Chaucha.

The deposit was discovered in 1968 by a regional stream sediment geochemical survey undertaken by the United Nations (UN, 1972).

Since its discovery the prospect has been investigated by a number of Government sponsored projects and commercial exploration ventures. Between 1970-1972 the Japanese Overseas Mineral Resources Development Corporation (OMRD) explored the deposit in detail and undertook an extensive drilling programme. From 1978 to 1986 the deposit was re-evaluated over a larger area by a Belgian mission (López et al., 1983; Misión de Bélgica, 1986). More recently several companies have reassessed the prospect for gold occurrences as well as copper mineralisation.

Surface exploration has defined six zones of primary mineralisation which take the form of vein stockworks and disseminations, but only the largest of these, the Naranjos zone, has been investigated in detail and drilled. A total of 107 boreholes have been drilled within this zone to depths of between 90-120 m, amounting 11170 m in aggregate. Most of this drilling was undertaken by the Japanese OMRD project with some additional work by the Belgian mission. OMRD estimated a resource of 55 million tonnes grading 0.57% Cu and 0.3% Mo. A more recent evaluation by EMIDEL calculated reserves of 40.89 million tonnes with 0.58% Cu at a cut-off grade of 0.4% Cu.

The deposit occurs near the margin of the Chaucha batholith. Mineralisation is hosted in tonalitic rocks close to, and around the contacts with later dacitic “quartz porphyry” intrusions, and within apophyses of quartz diorite and intrusive breccias. Mineralisation takes the form of disseminations, fracture coatings, quartz veinlets and locally occurs in stockworks. Vein mineralisation predominates in the central Naranjos zone, whereas the interiors of some satellite zones consist exclusively of disseminated sulphides.

The mineralisation is assumed to have been broadly coeval with the intrusion of the batholith. This has been dated at Chaucha by the K/Ar method which has yielded two ages of 12.5 ± 0.6 Ma (Snelling, 1970) and 9.77 ± 0.29 Ma (Müller-Kahle and Damon, 1970).

Goossens and Hollister (1973) published an early description of the Chaucha deposit and proposed that the porphyry system was controlled by the intersection of two major structures. These were an E-W structure, the Chaucha Fault, assumed to be aligned along the Río Angas, and a major NNE-SSW structure which was named the Cordillera Fault. The regional mapping of the present project found no evidence for such structures. However, several NE-SW semi-regional fractures cut across the area, and the fundamental NE-SW suture (Bulubulu Fault) which separates metamorphic rocks to the south-east from ocean floor basalts of the Pallatanga Unit to the north-west is situated a few-kilometres to the west of Chaucha and may have exerted some control over the emplacement of the batholith.

López et al. (1983) reported that hydrothermal alteration conforms to a concentrically zoned Lowell and Guilbert type model. They describe a large potassic core 3-4 km in diameter which is characterised by secondary biotite. This is reported to be surrounded by a phyllic zone of quartz-sericite alteration which overprints the potassic alteration, and which is in turn surrounded by an outer propylitic zone, 0.5 to 1 km wide, of chlorite-epidote alteration with carbonates and extensive pyritisation. Argillic alteration characterised by pervasive kaolinization is reported to be developed between the phyllic and propylitic zones only in the south-east, although other ill-defined zones of argillic alteration also occur elsewhere. Silicification is developed locally in the inner part of the propylitic zone and around breccia bodies. More recent commercial exploration indicates that the phyllic zone may be more extensive than previously reported by López et al. (op. cit.), extending throughout the north-east of the prospect. This extension may be related to a second smaller zone of potassic alteration associated with a diorite intrusion at Gur Gur. Tourmalinised breccias also occur. During the course of the present project hydraulically fractured tourmaline breccias were observed on the ridge above Naranjos at [6769-96757].

Primary ore-forming minerals include pyrite, chalcopyrite, molybdenite, bornite and minor sphalerite, pyrrhotite, magnetite, haematite and galena. An annular distribution of primary sulphides is reported to occur. The inner potassic alteration zone is barren. Chalcopyrite, bornite, molybdenite and pyrite occur at the potassic-phyllic transition and pass outwards through an assemblage of pyrite, chalcopyrite and molybdenite in the exterior of the phyllic zone, to pyrite, sphalerite, chalcopyrite and galena in the propylitic zone.

Secondary minerals include chalcocite, covellite, digenite, bornite, tenorite, cuprite, native copper, malachite, azurite, goethite and limonite.

Gold occurs in the Cu-rich zone and is associated with breccias, peripheral veining and areas of intense silicification.

The Naranjos body has a surface area of 45 ha. It is capped by a leached, oxidised gossanous zone 30-40 m thick, but locally reaching up to 100 m, which contains little copper except for minor amounts of native copper, tenorite and cuprite. This is underlain by a zone of supergene enrichment on average 60 m thick, but locally up to 100 m, containing covellite, bornite, chalcocite and digenite. Underlying this is a transitional zone of secondary enrichment which passes down into hypogene mineralisation consisting of pyrite, chalcopyrite, molybdenite, sphalerite and pyrrhotite.

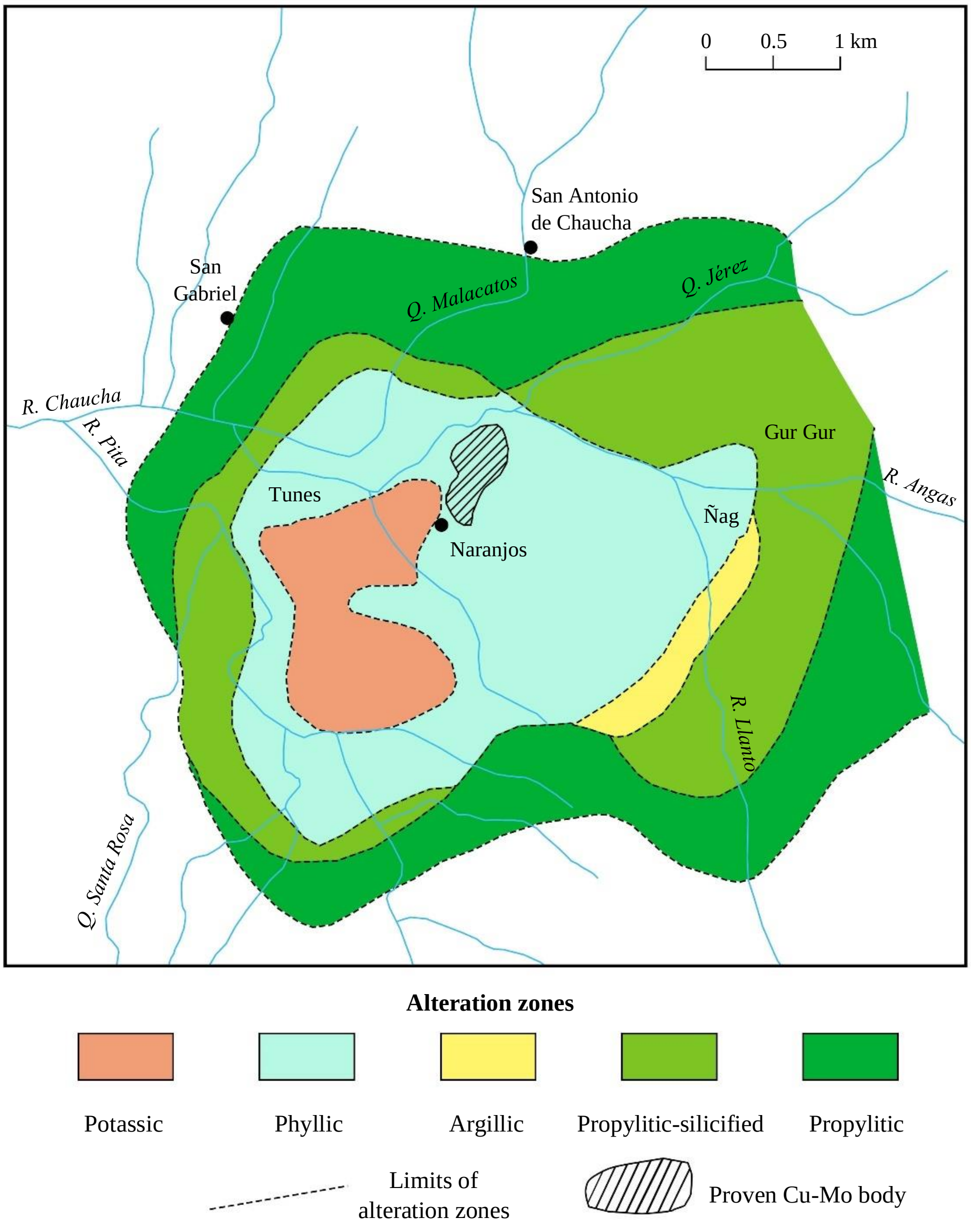


Figure 20. Map of the Chaucha porphyry copper prospect showing the main zones of hydrothermal alteration (after López et al., 1983)

The deposit has a pronounced surface geochemical signature. The present project detected a very strong Cu-Mo anomaly with a long dispersion train within the stream sediments of the Río Chaucha drainage system. Previous surveys have shown the presence of strong Cu and Mo anomalies in soils over the phyllic alteration zone, which surrounds a central sub-anomalous area corresponding to the sterile potassic core of the porphyry system. Copper anomalies are also located around Gur Gur, where they overlie phyllic alteration which possibly surrounds a satellite potassic zone. The Cu-Mo soil anomalies are surrounded by numerous concentrically-arranged Pb and Zn anomalies. Some spatial overlap occurs between Cu and Zn anomalies, but there is a strong antipathetic relationship between Zn and Mo. Zones of intense silicification are characterised by Au, Ag and W anomalies. In several areas scheelite occurs in stream sediment heavy mineral concentrates. The highest concentrations occur in the Río Malacatos, where López et al. (1983) report up to 10 grams of scheelite in heavy mineral concentrates within a single pan.

Geophysical prospecting has shown that a pyritic subzone (7-20% pyrite) corresponding to the silicified inner part of the propylitic zone yields an annulus of strong IP anomalies. Magnetic anomalies also occur within the pyritic subzone and over magnetite-bearing stockworks in the interior of the phyllic zone.

More recently the general area of Chaucha has attracted attention as a target for precious metal exploration. Gold mineralisation is reported to occur in satellite veins and shears surrounding the porphyry prospect. One example is a small but reputedly rich vein at approximately [6787-96730] which at the time of the present survey was being mined.

Strong silicification, veining brecciation and pyritization occur in the roof zone of the Chaucha porphyry system around Cerro Cascajo [6770-96755]. Tourmalinised breccias and stockworks occur at this locality. Other areas of strong alteration and pyritization occur higher up the ridge towards the settlement of Cascajo.

During the course of the present project numerous stream sediment geochemical anomalies were detected within the general area surrounding Chaucha. These include Au anomalies and several significant base-metal, Sb, As and Hg anomalies within the Río Chaucha and its main tributaries.

7.2.3 Mineralised breccias along the Chaucha-Angas road section

Several mineralised breccias were discovered during the present survey along the newly constructed road between Angas and Chaucha in the vicinity of the Río Jérez. These cross-cut dacitic and rhyolitic tuffs and lavas belong to the Saraguro Group. One good example of a mineralised tuffisite pebble dyke or pipe is exposed at [6820-96783]. It is composed of rounded and subrounded polymict volcanic clasts cemented by silica and sulphides. Primary minerals include pyrite and chalcopyrite and these are overgrown and cross-cut by secondary minerals including bornite, covellite, chalcocite, malachite and azurite.

7.2.4 Angas polymetallic mineralisation

Zinc anomalies in stream sediments led to the discovery of mineralisation in the high ground at the head of the Angas valley [6870-96810] during the first phase of a United Nations exploration project (UNDP, 1969). Seven strongly silicified breccia zones containing Ag, Cu, Pb, Bi and Sb mineralisation were subsequently discovered during a follow-up phase of the project (UNDP, 1972).

Additional exploration was undertaken on the prospect between 1976 and 1977 by the United Nations Revolving Fund. During this phase an exploratory adit was driven into the head of the valley, but in 1979 it was recommended that no further work be undertaken. Despite this recommendation, a Belgian mission continued exploration under the auspices of INEMIN, the findings of which were published in a brief description by Van Thournout and Guzmán (1988). A total of 18 breccia bodies of various types were described, including pebble dykes, breccia pipes and shatter zones containing polymetallic sulphides. These are associated with strong silicification and argillic alteration within broader zones of propylitic alteration. On the basis of the style of alteration it was concluded that the deposits were of epithermal origin of acid-sulphate type (high-sulphidation). The breccias were alleged to intrude rhyolites and quartz latites of the Tarqui Formation of probable Late Pliocene or Early Pleistocene age. Van Thournout and Guzmán (op. cit.) proposed that the breccia pipes mark the site of a caldera structure which was reputedly centred on the so-called Atugpamba intrusion at [6865-96835].

Even the cursory reconnaissance mapping of the present project has shown the identification of rock types and interpretation of volcanic structures by Van Thournout and Guzmán (1988) to be out-dated and speculative. Firstly, the host rocks of the breccias and mineralisation are welded dacitic tuffs, which belong to the Soldados Formation of Late Oligocene age. The so-called Atugpamba intrusion which reputedly formed the core of the volcanic centre is in fact an area composed of gently dipping welded ash-flow tuffs, which display obvious vitroclastic textures in outcrop. No structures nor lithofacies were found in the Angas area during the present work which would support the notion of a caldera structure as suggested by Van Thournout and Guzmán (op. cit.).

The present project discovered a new occurrence of quartz-tourmaline breccias and veinlets at the Angas prospect [6864-96825]. A cursory examination indicated the presence of pyrite and specularite in veinlets and on joint faces. Chemical analysis of a single sample indicates anomalous Ag (4.1 ppm), Pb (930 ppm), As (1225 ppm) and weakly anomalous Au (27 ppb), Cu (391 ppm), Sb (8.5 ppm) and Hg (0.082 ppm).

The regional drainage geochemical survey of the current project (Williams et al., 1998) also showed the stream sediments of the Río Angas and certain headwaters to be anomalous in Au, Ag, Cu, Pb, Zn, Cd, Bi, As, Sb and Hg.

7.2.5 The Río Blanco Au-Ag epithermal prospect

The Río Blanco prospect is situated on the high ground overlooking the northernmost headwaters of the Río Canoas. It is named after the small settlement located about a kilometre to the north-east of the prospect at [6819-96883].

Gold anomalies were discovered in stream sediments in the headwaters of the Río Canoas by Río Tinto Mining and Exploration Ltd. in 1996. Follow-up surveys indicated extensive hydrothermal alteration associated with Au-Ag mineralisation within the Migsihuigsi area [6795-96863] and extending northwards towards Río Blanco.

The mineralisation occurs within a broad N-S trending zone extending from the floor of the Canoas valley up to the top of the Migsihuigsi escarpment. From the top of the escarpment the mineralisation extends for a short distance farther northwards, occupying a broad dip-slope feature which is inclined gently towards the NNE into the headwaters of the Quebrada Río Blanco [6805-96882]. In the main escarpment the mineralisation appears to be confined between the Quebrada Migsihuigsi to the east and the Quebrada Malpapeada to the west. The surface mineralisation thus forms a zone approximately 800 m wide and 1.8 km long in a N-S direction, which ranges in altitude from about 2800 m in the Río Canoas in the south to about 3900 m at the top of the escarpment in the north.

The prospect falls within two concessions. These are the Canoas concession which covers the main part of the escarpment, and the San Luis concession which covers the top of the escarpment and dip-slope to the north. A detailed rock sampling and drilling programme was undertaken within the Canoas concession by Río Tinto Mining and Exploration in 1996 and 1997, whilst Ecuadorian Minerals Corporation (EMC) carried out surface exploration within the San Luis concession. In 1998 the Canoas concession was acquired from Río Tinto by EMC, which refers to the entire property as the Beroen deposit.

The mineralisation is hosted within andesitic volcaniclastic rocks and lavas of the Río Blanco Formation, which are intruded in the lower part of the escarpment by a diorite. The volcaniclastic rocks include welded ash-flow tuffs, reworked tuffs, epiclastic breccias, and volcanic sandstones. These generally strike NW-SE and dip gently to the NE, although the strata are somewhat disturbed within the mineralised area due to landsliding on the steep escarpment.

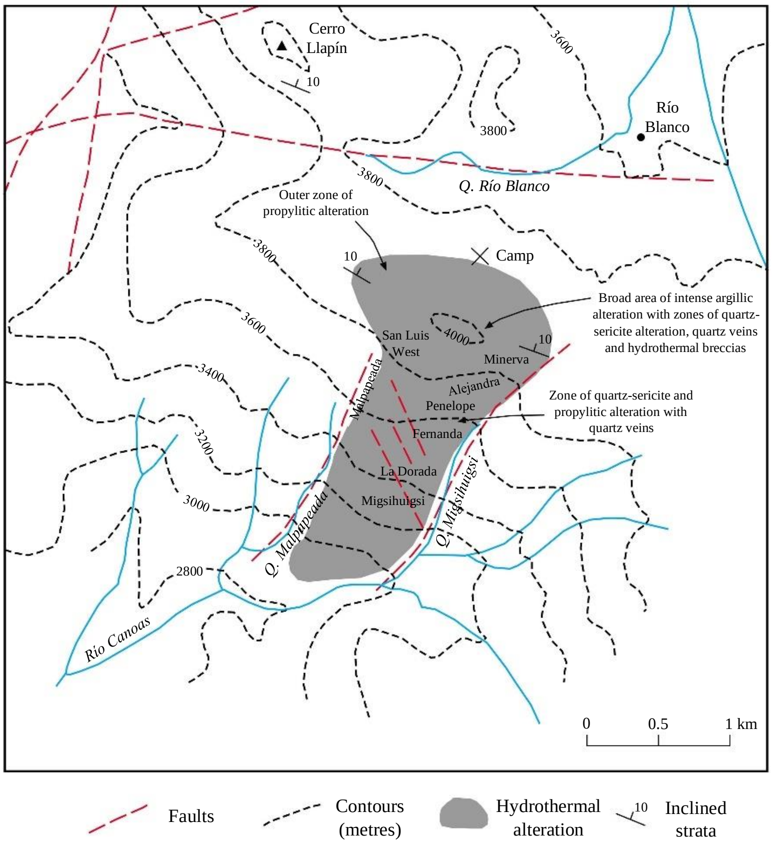


Figure 21. Map of the Río Blanco prospect showing the main area of hydrothermal alteration and the location of the various mineralised zones referred to in the text

Several fracture trends are apparent on aerial photographs. NNE-SSW lineaments are aligned along the Quebrada Migsihuigsi and the Quebrada Malpapeada. These are parallel to the principal regional fault trend, and the mineralisation is broadly confined between them. The main zone of mineralisation within the escarpment is traversed by a number of slightly curved NW-SE fractures, which have been interpreted as Reidel shears formed as a result of dextral strike-slip movement on the confining NNE-SSW fractures. However, these fractures may be related to a major (ancient) landslip, which is apparent on large-scale aerial photographs between the Quebrada Migsihuigsi and the Quebrada Malpapeada. At the top of the escarpment (and farther north) several large E-W faults are evident. A subcircular area of relatively unfractured terrain can be seen on aerial photographs in the area to the southeast of the prospect, and has been interpreted as a competent block which could possibly represent a concealed intrusion.

Surface rock sampling has delimited a number of zones with high Au and Ag concentrations which are also coincident with Induced Polarisation geophysical anomalies. From the base of the escarpment to the top (i.e. from south to north), these are the Migsihuigsi, La Dorada, Fernanda, Penelope, Alejandra and Minerva zones. Lower surface Au concentrations occur to the west in the Lourdes and San Luis West zones. Most of these zones occur within volcanic rocks of the Río Blanco Formation, except the Migsihuigsi and La Dorada zones which are underlain by both volcanic rocks and the diorite intruding them in the lower part of the escarpment.

The Au-Ag mineralisation occurs in zones of intense silicification and quartz veining. Within the escarpment the silicification and veins appear to be fracture controlled and enclosed within broader zones of pervasive propylitic (chlorite, epidote, pyrite) and quartz-sericitic alteration. At the top of the escarpment (+ 3850 m) and in the dip slope to the north, the alteration envelope opens out into a very broad zone of pervasive argillic alteration approximately 900 m wide from east to west and 600 m from north to south. This is characterised by illite and smectite assemblages, but also contains significant quartz-sericite alteration and is surrounded by a broad envelope of propylitic alteration.

The zones of silicification contain multi-stage quartz veinlets ranging from a few millimetres to centimetres in thickness, together with less common veins up to about a metre in width. In places the veining gives rise to stockworks.

At the top of the escarpment, within the Minerva and Alejandra zones, the veins trend E-W and NNE-SSW. The limited data available suggests that at lower elevations within the Dorada, Fernanda and Penelope zones the silicification and veins trend mainly NNE-SSW and are vertical to steeply dipping. Here the main feeder veins are discontinuous, with strike-lengths of a few 10's of metres. At lower topographic levels, within the Dorada and Migsihuigsi zones, only thin, widely-spaced quartz veinlets occur within the diorite.

The veins consist predominantly of quartz which varies in colour from pure white, to dark grey and ochreous yellow. Minor carbonate, chalcedonic quartz, chlorite, epidote, actinolite, tourmaline and traces of adularia have also been identified in the veins. Preliminary work has recognised at least five episodes of veining which show a range of textures. In hand specimen most veins have a fine-grained homogeneous appearance, although small-scale comb textures and internal grain-size variations are evident in thin section. Locally colloform banding occurs, and hydrothermal breccias are developed in the higher parts of the prospect within the Minerva and Alejandra zones.

Only limited mineralogical work has been undertaken to date. The mineralisation is generally sulphide-poor. Metallic minerals that have been identified include native gold, electrum, pyrite, arsenopyrite and the silver telluride hessite.

Gold grades within the zones of mineralisation are very variable and vary by several orders of magnitude over short distances. In general, Ag concentrations are several times higher than Au concentrations. Preliminary mineralogical work indicates that only certain phases of silicification carry high Au-Ag concentrations and that some phases are barren.

The average grades of surface rock samples from the various mineralised zones are summarised in Table 11. Maximum reported values for individual samples from the Minerva-Alejandra zone are 113 g/t Au and 541 g/t Ag, although average grades are an order of magnitude lower (EMC, 1998).

In 1997 Río Tinto Mining and Exploration drilled 47 holes totaling just under 6000 m in the Penelope, Fernanda and La Dorada zones, EMC reports a number of high-grade intersections near the surface, the best of which are 34.5 m grading 12.3 g/t Au (borehole LLP09) and 27 m grading 10.4 g/t Au (borehole LLP10) (EMC, 1998). In interpreting these preliminary drilling results, it should be noted that all the boreholes were vertical to steeply inclined, despite the fact that the mineralised structures also appear to be of this orientation. Furthermore, any future drilling on the escarpment should consider the possibility that structures may have been disrupted by landsliding.

Table 11. Average gold and silver concentrations in surface rock samples. From Ecuadorian Minerals Corporation (1998)

ZONE	No. Samples	Ave. Au g/t	Ave. Ag g/t
Migsihuigsi	342	1.1	-
La Dorada	130	6.0	-
Fernanda	109	0.6	-
Penelope	114	2.2	-
Alejandra	33	7.7	40
Minerva	32	14.5	59
Lourdes	85	0.4	-
San Luis West	50	0.9	-

Chemical analysis of surface rock samples undertaken by subcomponent 3.5 of the PRODEMINCA project suggests a geochemical zonation within the system. The prospect is generally characterised by low Au/Ag ratios and very low base metal concentrations. The property is also associated with anomalous As, Sb and Hg concentrations. In the case of Sb and As the concentrations appear to increase upwards within the system and to be associated with a decrease in Au/Ag ratios.

Overall, the deposit is interpreted as a low-sulphidation epithermal precious metal system which may be genetically related to the underlying diorite. Such a model would explain the upward increase in volatile elements and associated decrease in Au/Ag ratios. The NE-SW trending veins and zones of silicification within the lower to middle levels of the property are interpreted as fluid pathways, which open out into a much larger system at the top of the escarpment where the broad “cap” of argillic alteration is developed and where there is evidence of hydrothermal brecciation.

On the assumption that the mineralisation is genetically related to the diorite intrusion, and that this in turn represents an intrusive phase of the Chaucha batholith, the mineralisation is likely to be of Middle to Upper Miocene age.

7.2.6 Other zones of mineralisation near Río Blanco

Several other zones of mineralisation have been reported from the vicinity of Río Blanco. These may be part of the overall system related to the main Río Blanco deposit described in the previous section.

Ecuadorian Minerals Corporation (1997) indicates the presence of a zone of mineralisation in the vicinity of the Quebrada Río Blanco. This is named the Río Blanco zone and is reported to have values of up to 2.9 g/t Au and 78 g/t Ag in surface rock samples. Another zone, the Camp zone, occurs to the north-west and is reported to have weak surface rock gold anomalies.

During the course of geological mapping, strong silicification and pyritization were observed within the Río Blanco Formation at [6795-96887] near the base of the southern flank of Cerro Llapín. This could be part of the Camp zone described in the previous paragraph.

7.2.7 Mercury and gold anomalies over the Plancharumi Formation

During the present project a number of Au, Hg, Sb and As stream sediment geochemical anomalies were discovered in rivers draining the Plancharumi Formation. As described in Section 4.7.10, the formation consists of rhyolite lavas, tuffs, breccias and reworked volcanic sediments which were erupted and deposited within a lacustrine environment, in which there is evidence for phreatomagmatic activity. The presence of these anomalies taken together with the composition and style of volcanism within a lacustrine palaeo-environment are factors which make the Plancharumi Formation a target worthy of more detailed investigations.

Attention was first drawn to the area by the discovery of a strong mercury anomaly in the Río Bermejos [6978-96700] and Quebrada Trigo Loma [6980-96711]. Values of up to 19 ppm Hg were recorded in association with a dispersion train of decreasing anomalies downstream. Weak Hg anomalies occur elsewhere on the Plancharumi Formation and another significant anomaly occurs in the Río Yanuncay a short distance to the north of Cerro Plancharumi. Au anomalies also occur in these drainages, although coincident Au-Hg anomalies were only found in one sample. Coarse-grained free gold with morphological characteristics of a local provenance was also panned in the Quebrada Chanchán. As and Sb anomalies were also detected in the Quebrada Chanchán and farther down in the Río Pucán.

To the west of the Río Bermejos much of the formation is covered by thin peat and is very poorly exposed. Several Au anomalies were detected within this area, the highest occurring in the Río Quingoyacu. Still farther west in the Pimo area the rocks of the formation are strongly altered.

With the scant information available, it is not possible to provide a hypothesis for the cause of this broadly anomalous area. The presence of Au, Hg, As and Sb anomalies and the paleo-environment of the Plancharumi Formation suggest an epithermal origin. It is possible, but considered unlikely, that the Hg and Au anomalies are not directly related, since they are generally, not coincident within the same samples. The main Hg anomaly in the Río Bermejos occurs within the Plancharumi Formation just downstream from the unconformably overlying andesite lavas and breccias of the Quimsacocha Formation. Other Hg anomalies also occur around the periphery of the Quimsacocha Formation in the map area to the south. One explanation is that these locations would have been the structural and topographical positions where hot spring activity related to the Quimsacocha volcano could have occurred. It is therefore possible that the Hg anomalies within the Río Bermejos are related to mineralisation within the Plancharumi Formation formed by geothermal outflow (hot spring discharge) from the much younger Quimsacocha centre. Such a model does not however explain the Au mineralisation, nor the Hg anomalies in the Río Yanuncay.

7.2.8 Gold in the Río Soldados

Several Au geochemical anomalies were discovered in the stream sediments of the Río Soldados during the present survey, and visible gold was also observed in panned concentrates. The source of this gold is unknown. The valley itself is incised within dacitic ash-flow tuffs of the Soldados Formation and appears to be aligned along a NNW-SSE trending fault.

7.2.9 Polymetallic mineralisation near San Felipe de Molleturo

Several mineralised localities are known in the Molleturo area. These occur close to the contact of the Molleturo diorite.

Polymetallic quartz veins with Cu, Pb, Zn sulphides occur within the diorite intrusion close to its margin at [6794-96976] near Chaupiurcu. This mineralisation was discovered by the United Nations survey and occurs in quartz veins and veinlets which are reported to contain pyrite, chalcopyrite, enargite, bornite, covellite, malachite, galena and sphalerite.

7.2.10 Cu-Mo mineralisation at Miguir

A small area of disseminated chalcopyrite and molybdenite occurs in hornfelsed and silicified volcanic rocks immediately to the west of the bridge at Miguir [6888-96905]. The hornfelsing and mineralisation may be related to the Molleturo diorite, which outcrops to the west, although it could also be related to a concealed porphyritic granodiorite, a small outcrop of which occurs immediately to the east of the bridge.

7.2.11 Quartz veining in the Miguir-Cerro Negro-Filo Cajas area

A broad zone of quartz veining occurs to the north of Miguir, in the area between Cerro Parco [6865-96914] and the Quebrada Cerro Negro [6874-96940], and around Lagunas Playas Encantadas [6910-96945] and the southern end of Filo Cajas. The area was only examined in a cursory manner during the course of a few widely spaced geological traverses. Although little is known about this area, it is considered worthy of follow-up investigation.

The area is composed of tuffs and lavas of the Filo Cajas Unit which are intruded to the west by the Molleturo diorite. The interpretation of aerial photographs and satellite images suggests that a major E-W trending lineament runs along the Río Miguir and Río Huilda. At the eastern end the lineament splits into a number of splays which coincide with the quebradas Cerro Negro, Playas Encantadas and Río Huilda. On aerial photographs the eastern ends of these splays appear to end in strongly fractured zones of small closely spaced E-W trending fractures. The Quebrada La Chorrera, situated several kilometres to the north, appears to mark a similar line of E-W fractures. The geology of part of this area is complicated by what appears on aerial photographs to be a very large landslip, which is bounded to the north by the Río Huilda and Quebrada Cerro Negro, and to the south by the Río Miguir and Quebrada El Parco. A semicircular fracture along Cerro La Cabezone-Filo Cerco de Piedras and Cerro Negro is interpreted as the scar of the landslip.

The stream sediment geochemical survey of the project detected a number of Au anomalies in the quebradas of this area.

The footpath leading westwards from Miguir to Cerro Parco and then northwards to Quebrada Cerro Negro runs approximately along the contact between the Molleturo diorite and tuffs of the Filo Cajas Unit. From Cerro Parco northwards there are signs of mineralisation and Au anomalies occur in several quebradas. Where the path crosses the Quebrada El Parco [6870-96920] there is a small quartz monzonite intrusion with prominent pink K-feldspar phenocrysts. This appears to be a marginal phase of the Molleturo diorite. Passing northwards along the footpath into the diorite there are numerous quartz veins, some of which are associated with brecciation. These are particularly common in the area between Quebrada Trinidad and Quebrada Cerro Negro. The ground to the north of Quebrada Cerro Negro has neither been examined nor sampled during the present project.

A geological traverse was also undertaken through the area of Lagunas Playas Encantadas [6910-96945] and the southern end of Filo Cajas. Aerial photographic interpretation suggests this ground is fractured. A few quartz veins were seen around the lakes, and numerous small E-W trending quartz veins cut the southern end of the Filo Cajas around [6917-96948], some of which are reputed to carry anomalous Au values. The vein system appears to extend farther east of the Filo Cajas, with sporadic E-W veins occurring in the vicinity of the lakes around [6920-96945].

7.2.12 Mineralisation in the headwater catchment of the Río Patul

Several zones of mineralisation were discovered in the headwater catchment of the Río Patul during the course of geological mapping.

A zone of widely-spaced, thin quartz veins and weak hydrothermal alteration occurs at the western end of Laguna Sisarín [7002-97012]. The veins are hosted within welded rhyodacitic ash-flow tuffs at the top of the Chulo Unit, just beneath the unconformity with overlying andesite lavas of the Chanlud Formation. They trend E-W and are vertical to steeply dipping, and range up to a few 10’s of centimetres in width. A large rhyolite intrusion occurs immediately to the south and east and intrudes both the Chulo Unit and Chanlud Formation. Silicified rhyolitic breccias also occur to the south-west of the lake. These were not examined in detail, although iron staining seen from a distance suggests they may be mineralised.

Although the veining at this locality is not particularly intense and no sulphides were seen, the locality merits further investigation because the stream sediments of the Quebrada Chocarhuaycu, which drains the veined area, have anomalous Au-Ag geochemical values. An anomaly was also detected in the Río Curiquinga [69955-969932] which drains the south side of the rhyolite intrusion.

Intense silicification and brecciation with extensively developed iron staining occur around [6961-97051].

The visually most impressive and extensive zone of mineralisation within the Patul area occurs within the dacitic and rhyolitic tuffs of the Filo Cajas Unit to the west of Cerro Ventanillas at [6935-97005]. This takes the form of strong silicification with quartz veinlets and pyrite. Impressive iron staining associated with the mineralisation occurs within cliffs at [6935-97006], but this was not examined due to lack of time and inaccessibility. The upper levels of this mineralisation were examined in a cursory manner adjacent to the footpath. Here multi-stage quartz veinlets and brecciation occur. Two grab samples of silicified rock were found to contain very low base metal concentrations and Au and Ag values below detection, but were anomalous in As and Hg (values of 0.155 and 0.519 ppm Hg).

A significant Au anomaly was discovered in stream sediments to the west of the previously described locality in the western branch of the Río Patul. There is no coincident enrichment in pathfinder elements associated with this anomaly. The locality was not visited during the geological mapping, but occurs in an area designated as dacitic and rhyolitic tuffs of the Filo Cajas Unit, which are intruded by a diorite forming the summit peak of Huahualcay.

7.2.13 Mineralised zones within the Chanlud Formation

Several zones of mineralisation were encountered within the andesitic lavas of the Chanlud Formation during the course of the present survey. Most of these occurrences appear to be associated with NW-SE fractures or faults, and to a lesser extent NE-SW fractures.

The largest of these zones occurs at Cerro Alumbre [7130-97080], situated approximately 6 km to the north-west of the Represa Chanlud (Plate 21). Access to the area may be gained by road as far as the dam at Chanlud, and from there on foot to Cerro Alumbre. The area was only examined in a cursory manner during the course of a geological traverse. The mineralisation consists of intense pyritization associated with silicification, hosted in horizontal andesitic lavas and breccias. A locality was examined on the south side of the mountain at [7135-97076]. Here the rocks are strongly silicified and pyritised. The silicification takes the form of pervasive alteration and multiphase veinlets and is associated with breccias formed by hydraulic fracturing or hydrothermal brecciation. Three grab samples of silicified and pyritised rock were unsystematically collected for chemical analysis. All contained subanomalous concentrations of base and precious metals, but were anomalous in As and weakly anomalous in Hg (0.056-0.427 ppm). The alteration extends for more than a kilometre along the southern side of the mountain. The adjacent valley floor of the Río Machángara is occupied by a large area of highly ferruginous bog (Plate 22 and 23). At least some of the colloidal hydrated oxides are derived from the oxidised pyrite of Cerro Alumbre, but if the mineralisation is fault controlled then the main zone of mineralisation may underlie the bog along the line of a concealed fault which is believed to run along the valley.

To the south-east of the Represa Chanlud, silicification and argillic alteration are associated with pyrite at [7224-96995]. This mineralisation is located on the same fault line as that at Cerro Alumbre. It occurs approximately at the contact between the lavas of the Chanlud Formation and underlying tuffs of the Tomebamba Unit. The mineralisation is exposed in several landslips which are drained by small tributaries which have base metal stream sediment geochemical anomalies.

Similar alteration and pyritization occurs within the lavas of the formation on the road to the Represa Labrada between [7200-96969] and [7184-96980] in the Chulco valley.

Pyritization and silicification were also observed within the lavas adjacent to the footpath at [7073-96990] between Laguna Yanacocha and Cerro Santa Rosa. This was not examined and its extent is therefore unknown.

Two other small zones of pyritization occur within the lavas of the Chanlud Formation in the headwaters of Río Ventanas at [7110-97116] and [7123-97124].

A number of stream sediment geochemical anomalies were discovered during the course of the project in rivers draining the Chanlud Formation. Five small Au anomalies were discovered in the Río Chulco drainage system Pb, Zn and As anomalies occur in the upper reaches of the Río Corazón.

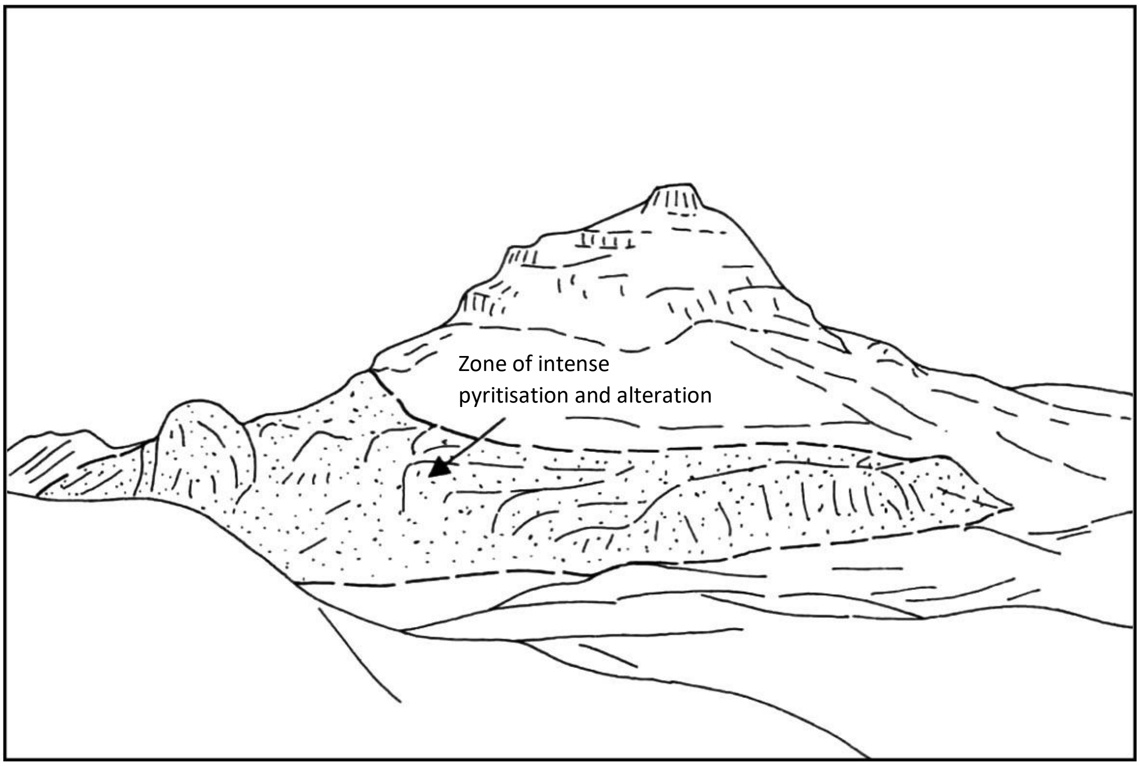


Plate 21. Cerro Alumbre viewed from the south-east

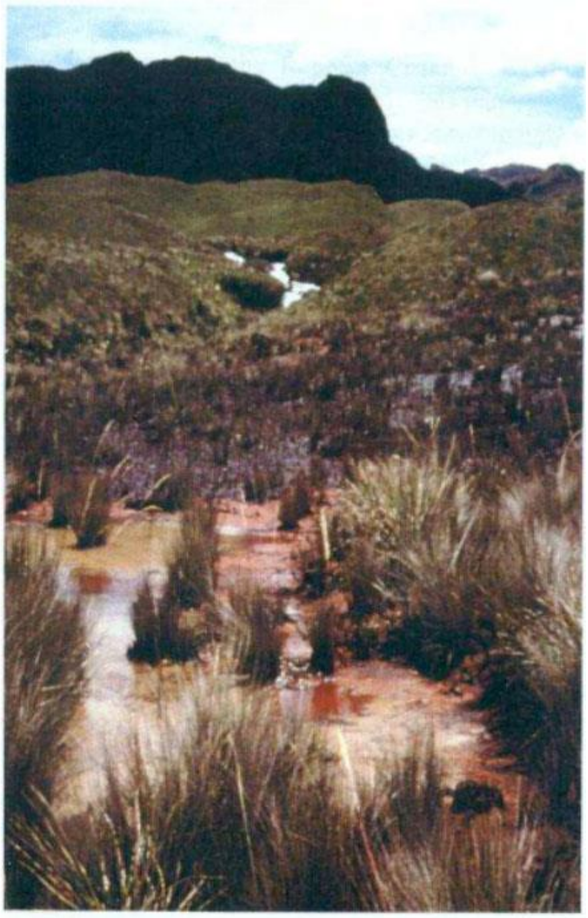


Plate 22 and 23. Ferruginous bog on the southeastern side of Cerro Alumbre

7.2.14 Polymetallic mineralisation on the south side of the Río Cañar

A number of occurrences of polymetallic Au, Ag, Pb, Zn, Cu mineralisation are reported from a broad area along the south side of the Río Cañar in the sectors of Gualleturo, Rosario [7035-97225], Ger [7167-97227], Malal [7195-97160] and Purubin [7126-97171].

Several zones of mineralisation were discovered in this region by the United Nations (1972) and these have subsequently been investigated by commercial exploration ventures. Very little recorded information is available on the mineralisation of this region, except that it is generally said to be of epithermal character (e.g. Palacios, 1994). However, the origin and style of mineralisation at each of these widely spaced prospects are unlikely to be the same, given the variability of the geology of the region.

The sector that has been investigated most is that of Ger, where anomalies in Au, Ag, Pb, Cu, Zn, Mo and As occur. The mineralisation is reported to take the form of silica veinlets containing abundant pyrite. Mapping in this area during the present project discovered a group of coalesced rhyolite domes, which are intruded into andesitic and dacitic tuffs assigned to the Tomebamba Unit. The most prominent and well-preserved dome occurs immediately to the north-west of Ger at [7168-97228] and may be related to the mineralisation. It should be noted however, that the geology in the vicinity of Ger has been disrupted by a large (ancient) debris avalanche on which the settlement is built.

Several exposures of mineralisation within propylitically altered intermediate tuffs of the Tomebamba Unit occur along the road leading westwards from Ger to the bridge across the Río Cañar. These consist of zones of silicic and argillic alteration and brecciation containing disseminated pyrite. The most intense of these zones can be seen a short distance to the south of the bridge at [7126-97236] on the road leading to San Francisco de Gualleturo. A multi-element stream sediment geochemical anomaly (Zn, Pb, Ag, As, Sb and Hg) was also discovered near Ger in the Río de Raura [7148-97215]. The geology of this catchment was not examined, but the river contains hornblende diorite float which is pyritised and has traces of chalcopyrite.

Farther west towards San Francisco de Gualleturo, minor artisanal gold workings occur in the Quebrada Osoyacu. A small Au stream sediment geochemical anomaly was found within the stream sediments of the quebrada.

A polymetallic base and precious metal stream sediment geochemical anomaly was also discovered a few kilometres to the south-west of Gulag Bajo in the Río Corazón at [7039-97203]. This site occurs at the contact between a granodiorite intrusion and silicified dacitic tuffs. Other base and precious metal anomalies were also discovered in the headwaters of this drainage basin (see Williams et al., 1998).

To the south-west of San Antonio de Gualleturo a strong Au anomaly was detected in the stream sediments of the Quebrada de Las Ánimas. The highest value occurs near Chaupiyunga [6999-97208], from where a dispersion train of diminishing anomalies extends downstream. The bedrocks in this area consist of pyritised tuffs which are assigned to the Ocaña Formation.

Farther south and at a higher altitude, epithermal mineralisation is reported to occur in the Purubín sector [7126-97171]. High Ag, Pb, Cu and Zn anomalies are reported from veinlets and hydrothermal breccias within dacites and rhyolites. Geological mapping suggests that this area is not composed of dacitic and rhyolitic rocks, but of andesite lavas of the Chanlud Formation.

During the course of geological mapping, mineralisation was observed near Shuya. The locality occurs at [7181-97203] where the footpath to Ger leaves the bend in the road shortly before Shuya. The mineralisation takes the form of silicification and quartz veinlets, including chalcedonic quartz, with pyrite and possibly arsenopyrite. The original nature of the rock is difficult to identify because of the silicification. In the field the rock appears to be a tuff, although the area has been mapped as Chanlud Formation.

7.2.15 Epithermal silver mineralisation at Achupallas

An intrusive rhyolite dome occurs at Achupallas, which is situated on the main road approximately 5 km south-east of Suscal. This dome intrudes andesite lavas of the Chanlud Formation and probably belongs to the same set of rhyolite intrusions described from the Ger area on the south side of the Río Cañar (see previous section). The top of the dome is exposed in a roadside quarry at [7135-97269]. Here it is strongly brecciated and silicified and contains abundant iron oxide on fracture surfaces and in veinlets, which is presumed to have replaced oxidised sulphides. The mineralised rhyolite is reported to contain high Ag values. During the present project two grab samples of mineralised rhyolite were collected in an unsystematic manner. These contained weakly anomalous Ag concentrations of 2.3 ppm and 5.3 ppm, but moderately anomalous Hg values of 0.619 ppm and 12.007 ppm, as well as anomalous As and Sb concentrations.

7.2.16 Hydrothermally altered rocks west of Ducur

A poorly exposed zone of hydrothermal alteration consisting of kaolinitized rocks with sulphides and sulphates occurs along the Zhud-La Troncal road to the west of Ducur between [7076-97291] and [7063-97485].

7.2.17 Hydrothermally alteration near Chunchi

A moderately large area of hydrothermal alteration consisting of clays stained yellow with sulphates occurs along the Panamerican highway near Chunchi, between [7313-94476] and [7332-97485]. This occurs within lavas and breccias of the Cisarán Formation.

7.3 Industrial minerals

7.3.1 Kaolin

Kaolin is mined in small quantities from the deeply weathered tuffs of the Tarqui Formation at [7078-96738], approximately 8 km south-west of Baños de Cuenca.

7.3.2 Sulphur

Sulphur has been mined near Tixán at the Mina de Shucos [7417-97612]. The mineralisation is hosted in andesite-dacite lavas of the Cisarán Formation cut by zones of intense silicification with abundant pyrite, sulphates and native sulphur. The mine produced 1188 tons of fine sulphur prior to its abandonment in 1971. In more recent years the mine has been explored for precious metals.

7.3.3 Travertine

Travertine is produced as an ornamental stone from the quarries at Mina Santa Rosa [7246-96945] situated approximately 7 km north east of Chiquintad. The travertine represents fossil hot spring deposits at the contact between sediments of the Cuenca Basin and andesitic lavas and tuffs of the Saraguro Group. The contact between the two rock types appears to be a thrust, with the sediments of the basin having been thrust westwards over the Saraguro Group.

7.3.4 Sand and gravel

Sand and gravel are produced in small amounts from various local workings in alluvial deposits.

7.3.5 Hard rock for aggregates

Hard rock is quarried locally for road construction. The largest quarry in the area is located in the andesitic-dacitic tuffs of the Tomebamba Unit at [7023-96932] on the side of the main road through the Cajas recreational park. This quarry was developed at the time of the mapping survey to provide aggregate for building the road, and later to supply other road construction schemes around Cuenca.

8. GEOLOGICAL HISTORY

Metamorphic rocks are the oldest of the area and form a basement to the younger volcanic cover throughout the region to the south-east of the Bulubulu Fault. These are predominantly low-grade metasedimentary rocks, the protolith of which consisted mainly of bedded siltstones, mudstones and sandstones, as well as conglomerates. High-grade schistose and gneissic rocks also occur, particularly near the margins of granitoid intrusions. These together with the occurrences of blue quartz-bearing metagranites near Huigra and garnetiferous orthogneisses just to the south of the mapped area indicate that the metamorphic basement is relatively complex. Such complexity accords with the hypothesis of Litherland et al. (1994) that much of the area is probably underlain by Late Paleozoic metasedimentary rocks of the Chaucha Terrane, which was affected by a Triassic orogeny.

The Mid- to Late Cretaceous Pallatanga Unit consists predominantly of submarine basalts which have MORB-like geochemical signatures. These are considered to represent part of an ophiolitic sequence that was accreted against the margin of the South American continent in the Late Cretaceous. The suture line for this accretion within the area is marked by the Bulubulu Fault, which separates the metamorphic rocks to the south-east from the basalts of the Pallatanga Unit to the north-west. A number of lines of indirect evidence suggest a Campanian age for this accretion. These include widespread resetting of isotopic ages in pre-Cretaceous rocks of the Cordillera Real between 85-65 Ma, which is believed to have been caused by uplift in response to the earliest accretionary events of the Western Cordillera (Aspden et al., 1992). Stratigraphical evidence for the emergence of a proto-Cordillera Real in the Late Cretaceous is also provided by contrasting sedimentary environments on either side of the cordillera, with Maastrichtian marine turbidites of the Yunguilla Unit accumulating to the west, and red-beds of the Tena Formation to the east (Baldock, 1982).

The Maastrichtian marine turbiditic fan sequence of the Yunguilla Unit was laid down at least in part upon the accreted oceanic terrane of the Pallatanga Unit. Petrographic evidence indicates that sediment was derived from a metamorphic source area, which was presumably being eroded as the proto-Cordillera Real formed to the east. Evidence for instability during the accumulation of the Yunguilla Unit is provided by large-scale slump structures and soft-sediment folds within the turbidites and widespread occurrences of intraformational debris-flow deposits. The local occurrence of basaltic volcaniclastic material within the unit in the south-west also indicates a basaltic volcanic source which may have been active at the time of deposition.

The Macuchi Unit consists of basaltic and andesitic volcanic rocks of Early to Middle Eocene and probably Palaeocene age. The rocks of the unit are of tholeiitic to transitional calc-alkaline affinity and have trace element characteristics compatible with formation within an immature intra-oceanic island arc setting. The rocks of the unit accumulated within a submarine environment in which much material was transported and deposited by mass-flow processes, although there is widespread evidence that pyroclastic material and some lavas were probably erupted in shallow water, and that conceivably some pyroclastic activity could have been subaerial.

The Palaeocene-Eocene siliciclastic basin-fill sequence of the Angamarca Group was probably laid down in a forearc-marginal sea which separated the Macuchi island arc from the continental margin. In the latest Eocene the Macuchi Arc was accreted obliquely onto the continental margin and translated northwards, deforming the Angamarca Group and Yunguilla Unit, and in places tectonically emplacing slices of the Pallatanga basalts into the Yunguilla sediments. The Chimbo-Cañi Fault Zone marks the suture line of this second accretionary event within the area, separating the Macuchi Unit to the north-west from the Angamarca Group and older lithotectonic units to the south-east.

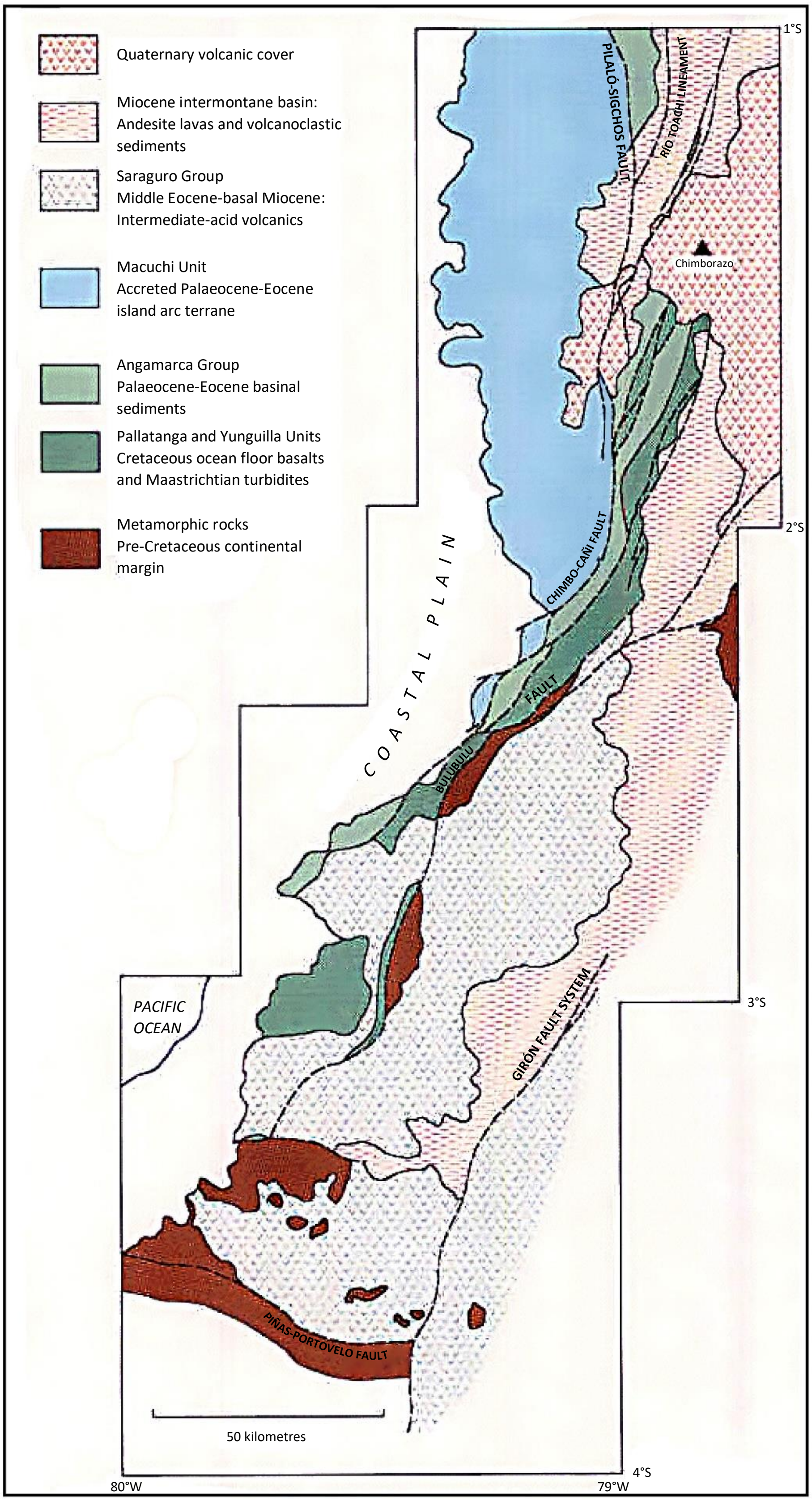


Figure 22. Simplified geotectonic map of the Western Cordillera of Ecuador between 1°-4°S

Subduction-related calc-alkaline continental margin volcanism of the Saraguro Group commenced in the latest Middle Eocene times and continued through to the Early Miocene. The volcanic products were deposited upon a basement of metamorphic rocks and sheared oceanic basalts of the Pallatanga Unit. During this prolonged period of activity there were numerous volcanic events of contrasting character and composition separated by periods of deformation and erosion. The products of at least eleven such events have been recognised within the Saraguro Group of the area. The earliest activity was characterised by the eruption of large-scale dacitic and rhyolitic pyroclastic flows and lavas during the latest Middle to Late Eocene and is represented by the Ocaña Formation, Chulo Unit and Filo Cajas Unit.

The occurrence of ash-flow tuffs within the Angamarca Group, which are of the same age and composition as the earliest dated ash-flow tuffs of the Saraguro Group, suggests that pyroclastic flows of the Saraguro activity flowed into the Angamarca sedimentary basin from the east. This implies that the volcanic activity of the Saraguro Group commenced before the accretion of the Macuchi island arc which caused the closure and deformation of the Angamarca basin.

At the end of the Eocene or possibly the very beginning of the Oligocene, the dacitic and rhyolitic volcanic units of the Ocaña Formation, Chulo Unit and Filo Cajas Unit underwent a period of deformation and erosion prior to eruption and deposition of the unconformably overlying andesitic ash-flow tuffs of the Tomebamba Unit. The eruption of the Tomebamba tuffs heralded the onset of a distinctly more andesitic phase of activity within the Saraguro Group, which continued through the Early Oligocene. Lithostratigraphic units formed during this phase of predominantly andesitic activity include the Tomebamba Unit, Río Blanco Formation and Chanlud Formation.

Voluminous andesite lavas were erupted over an extensive area during Chanlud Formation times. These were associated with the injection of a NW-trending dyke swarm which indicates that a NE-SW tensional stress regime coincided with this phase of activity. Such a regime may have developed in response to dextral strike-slip movement along the principal NE-trending terrane boundary faults, which because of their curvature in this sector of the cordillera could have generated pull-apart structures within the continental margin. It is proposed that the end Eocene-basal Oligocene deformation of the earlier dacitic-rhyolitic volcanic units of the Saraguro Group coincided with the final collision and accretion of the Macuchi island arc. Dextral strike-slip movements along the boundary faults as a result of continued northward translation of the Macuchi terrane are believed to have generated a tensional pull-apart structural regime to the south-east of the Bulubulu Fault which facilitated the rapid accent of less evolved andesitic magmas. In Chanlud Formation times this structural setting was sufficiently well-developed for the formation of dyke swarms and the rapid effusion of large volumes of lava.

By Late Oligocene times the Saraguro Group activity reverted once more to acid volcanism, characterised largely by the eruption in the Late Oligocene and Early Miocene of large-scale pyroclastic flows of the Soldados Formation (dacitic), and the Cerro Caucay, Plancharumi and Jubones formations (which are all rhyolitic), separated by periods of deformation and erosion.

In the Early Miocene (ca. 18 Ma) E-W tension resulted in the formation of intermontane basins, including the Cuenca Basin along the eastern margin of the mapped area. Fluvial sediments of the Early to Middle Miocene Ayancay Group and Late Miocene Turi Formation were deposited within the Cuenca Basin.

During the Late Miocene, andesite lavas were erupted in the south of the area from the Quimsacocha stratovolcano, situated just to the south of the map boundary. A large-scale pyroclastic event, characterised by ash-flows and ash-falls, produced the acid tuffs of the Tarqui Formation shortly after the Quimsacocha activity. In the north of the area large volumes of andesite-dacite lavas and lesser amounts of acid tuffs and pumice deposits of the Cisarán Formation were also erupted during the Late Miocene. A thick sequence of very coarse detrital volcanoclastic rocks is intercalated with the Cisarán lavas and appears to have accumulated largely in a fluvial environment with the local development of lacustrine facies.

During the Quaternary the high parts in the south of the area were glaciated. In the north of the area young volcanic ashes blanket the terrain, and in the extreme north-east, between Tixán and Palmira, pumiceous deposits, ashes and diatomites of the Palmira Formation were deposited in a fluviolacustrine basin. Pumiceous pyroclastic flow deposits (ignimbrite deposits) also occur within the valleys as far south as Alausí and are believed to have been erupted from one of the major Quaternary stratovolcanoes in the Riobamba area.

9. ACKNOWLEDGEMENTS

The authors wish to thank the numerous drivers who assisted us with fieldwork, including Hermes Chanchay, José (Pepino) López, Daniel Obando, Walter Obando, José Sanchez and Patricio Vega, all of whom provided good company on the road and managed to maintain a string of less than reliable vehicles. Special thanks are extended to the family of Don Gerardo Pelaez of Chulo, who acted as guides in the more remote parts of the Cajas area, and on numerous cold evenings shared their hearth and plied us with many a warming canelazo. Student geologist Vinicio Ortiz accompanied us on several field traverses and assisted with a range of tasks in the office. He undertook this work with energy, enthusiasm and good humor, and demonstrated a capacity for free thinking and original ideas. Fabiola Alcocer is thanked for her secretarial support during the course of the project. Finally, we would like to acknowledge our colleagues Richard Hughes, Bill McCourt, and Warren Pratt for stimulating discussions on the geology of the region.

10. BIBLIOGRAPHY

ASPDEN J. A., BONILLA W. and DUQUE P. (1995) The El Oro metamorphic complex, Ecuador: geology and economic mineral deposits. *Overseas Geology and Mineral Resources,* No. 67, 63 pp.

BALDOCK J. W. (1982) Geología del Ecuador. Boletín de la Explicación del Mapa Geológico (1:1000000) de la República del Ecuador. Ministerio de Recursos Naturales y Energéticos. Quito, 54 pp.

BRISTOW C. R. (1981) An annotated bibliography of Ecuadorian Geology. Institute of Geological Sciences, Overseas Memoir 58, London.

BRISTOW C. R. and HOFFSTETTER R. (1977) Lexique Stratigraphique International, Ecuador. Second edition. Paris: Centre National de la Recherche Scientifique.

BRISTOW C. R. and PARODIZ J. J. (1982) The stratigraphical palaeontology of the Tertiary non-marine sediments of Ecuador. *Bulletin of Carnegie Museum of Natural History,* 19. 1-53 (Pittsburgh, Pennsylvania).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (1993a) National geological map of Ecuador, scale 1:1000000. (Keyworth, Nottingham; BGS, and Quito; CODIGEM).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (1993b) National tectono-metallogenic map of Ecuador, scale 1:1000000. (Keyworth, Nottingham; BGS, and Quito; CODIGEM).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (1998a) Geological map of the Western Cordillera, Ecuador between 1 and 2 degrees south. (1:200000). (BGS, Nottingham; CODIGEM, Quito).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (1998b) Geological map of the Western Cordillera, Ecuador between 2 and 3 degrees south. (1:200000). (BGS, Nottingham; CODIGEM, Quito).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (1998c) Geological map of the Western Cordillera, Ecuador between 3 and 4 degrees south. (1:200000). (BGS, Nottingham; CODIGEM, Quito).

BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (In press) Geological map of the Western Cordillera, Ecuador between 0 and 1 degrees south. (1:200000). (BGS, Nottingham; CODIGEM, Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1975a) Mapa geológico del Ecuador, Alausí, Hoja 71 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1975b) Mapa geológico del Ecuador, Cañar, Hoja 72 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1979) Mapa geológico del Ecuador, Bucay, Hoja 51 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1980a) Mapa geológico del Ecuador, Gualleturo, Hoja 52 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1980b) Mapa geológico del Ecuador, Cuenca, Hoja 53 (1:100000). (Quito).

DIRECCIÓN GENERAL DE GEOLOGÍA Y MINAS (1980c) Mapa geológico del Ecuador, Azogues, Hoja 73 (1:100000). (Quito).

EGÜEZ A. (1986) Evolution Cénozoïque de la Cordillère Occidentale Septentrionale d'Equateur (0°15'S o 1°10'S). Les mineralisation associées. Unpublished PhD. Thésis, Université Pierre et Marie Curie, Paris, 116p.

EGÜEZ A., CAJAS M. and DAVILLA F. (1988) Distribución de terrenos oceánicos alóctonos y de terrenos continentales en la Cordillera Occidental del Ecuador: evidencias en las geotravesías Otavalo-Selva Alegre y Cañar-La Troncal. Politécnica. Monografía de Geología, Vol. 6, Part. XIII, No. 3, 101-136, Quito.

EGÜEZ A., DUGAS F., BONHOMME M. (1992) Las Unidades Huigra y Alausí en la Evolución Geodinámica del Valle Interandino del Ecuador. Boletín Geológico Ecuatoriano, 3, 47-56.

EMC (1997) High grade gold mineralisation reported by Ecuadorian et Beroen, Ecuador. New release of Ecuadorian Minerals Corporation, October 1, 1997. Internet site www.emcinfo.com/emc.

EMC (1998) Ecuadorian to acquire Río Tinto concessions and hold 100% interest at Beroen Gold/Silver property, Ecuador. News release of Ecuadorian Minerals Corporation, June 10, 1998. Internet site www.emcinfo.com/emc.

ERAZO M. T. (1957) Apuntes sobre la geología y estructura del Valle de Cuenca. *Anales de la Universidad de Cuenca.* Vol. 13, 157-197.

FAUCHER B. and SAVOYAT E. (1973) Esquema Geológico de los Andes Ecuatorianos. *Revue de Géographie et de Géologie Dynamique (2),* XV, Fase 1-2, 115-142. Paris.

GANSSER A. (1973) Facts and theories on the Andes. *Journal of the Geological Society of London*, 129, 93-131.

GILL J. B. (1978) Role of trace element partition coefficients in models of andesite genesis. *Geochimica et Cosmochimica Acta.* 42, 709-724.

GOOSSENS P. J. and HOLLISTER V. G. (1973) Structural control and hydrothermal alteration pattern of Chaucha Porphyry Copper, Ecuador. *Miner. Deposita.* Vol. 8, 321-331.

GOOSSENS P. J. and ROSE W. I. (1973) Chemical composition and age determination of tholeiitic rocks in the Basic Igneous Complex, Ecuador. *Bulletin of the Geological Society of America*, 84, 1043-1052.

HENDERSON W. G. (1979) Cretaceous to Eocene volcanic arc activity in the Andes of northern Ecuador. *Journal of the Geological Society of London*, Vol. 136, 373-378.

HENDERSON W. G. (1981) The volcanic Macuchi Formation, Andes of Northern Ecuador. *Newsletter in Stratigraphy,* **9**, *157-168.*

HUGHES R. A. and BERMÚDEZ R. A. (1997) Geology of the area between 1 degree south and the Equator, Western Cordillera, Ecuador. Report No. 4. Open File Report WC/97/25. British Geological Survey.

HUNGERBÜHLER D. (1997) Neogene basins in the Andes of Southern Ecuador: evolution, deformation and regional tectonic implications. Unpublished PhD thesis, Institute of Geology, ETH Zürich, Switzerland.

HUNGERBÜHLER D. and STEINMANN M. (1996) Curso internacional geología de cuencas sedimentarias (Mioceno, Sur del Ecuador), Guía de campo, *Escuela Politécnica Federal de Zürich,* 27 pp.

KENNERLEY J. B. (1973) Geology of Loja Province Southern Ecuador. Institute of Geological Sciences. *Overseas Geology and Mineral Resources, Photogeological Unit,* No. 23, 34 pp.

KENNERLEY J. B. (1980) Outline of the geology of Ecuador. Institute of Geological Sciences. *Overseas Geology and Mineral Resources,* No. 55, 20 pp.

LAVENU A., NOBLET C., BONHOMME M. G., EGÜEZ A., DUGAS F. and VIVIER G. (1992) New K-Ar age dates of Neogene and Quaternary volcanic rocks from the Ecuadorian Andes. Implications for the relationship between sedimentation, volcanism and tectonics. Journal of South American Earth Sciences. Vol. 5, part 3/4, 309-320.

LE MAITRE R.W. (ED.), BATEMAN P., DUDEK A., KELLER J., LAMEYRE J., LE BAS M. J., SABINE P. A., SCHMID R., SØRENSEN, STREKEISEN A., WOOLLEY A. R. and ZANETTIN B. (1989) A classification of igneous rocks and glossary of terms. Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. Blackwell Scientific Publications, Oxford, 196 pp.

LEBRAT M. (1985) Characterisation Géochimique du volcanisme ante-orogénique de l'occident équatorien: implications géodynamiques. Unpublished PhD thésis, Centre Géologique and Géophysique de Montpellier, Paris.

LITHERLAND M., ASPDEN J. A. and JEMIELITA R. A. (1994) The metamorphic belts of Ecuador. *Overseas Memoir of the British Geological Survey,* No. 11.

LONSDALE P. (1978) Ecuadorian subduction system. *Bulletin of the American Association of Petroleum Geologists, 62, 2454-2477.*

LÓPEZ E., MERLYN M., PUIG C. and VAN THOURNOUT F. (1983) Chaucha: Caso típico del modelo clásico de pórfido cuprífero. Unpublished Report, INEMIN, Quito, 31 pp.

McCOURT W. J., DUQUE P. and PILATASIG L. (1997) Geology of the Western Cordillera of Ecuador between 1-2°S. CODIGEM-BGS, Quito, Ecuador.

MEGARD F., LEBRAT M. and MOURIER T. (1986) Las suturas entre bloques exóticos y continental en el Ecuador y el norte del Perú. *Comunicaciones,* 3, 17-30.

MESCHEDE M. (1986) A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram. Chemical Geology, 56, 207-218.

MINISTERIO DE RECURSOS NATURALES Y ENERGÉTICOS e INSTITUTE OF GEOLOGICAL SCIENCES (MRNE-BGS) (1982) Mapa Geológico Nacional de la República del Ecuador. Escala 1:1000000, Quito.

MISIÓN BELGA (1986) Informe Final. Estudio del yacimiento de cobre porfídico de Chaucha, Ecuador. *Open File Report, INEMIN,* Quito, 334 pp. (unpublished).

MÜLLER-KAHLE E. and DAMON P. E. (1969) K-Ar age of a biotite granodiorite associated with primary Cu-Mo mineralization at Chaucha, Ecuador. In Damon, P. E. (Editor). Correlation and chronology of ore deposits and volcanic rocks. United States Atomic Energy Commission. Annual Progress Report CCO-689-130. University of Arizona, Tucson, 46-48.

NAKAMURA N. (1974) Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica Cosmochimica Acta.* 38, 757-775.

PALACIOS W. (1994) Mineralización en el sector de El Rosario. Memorias 4, Jornadas en Ciencias de la Tierra, 80-81.

PEARCE J. A. (1975) Basalt geochemistry used to investigate past tectonic environments on Cyprus. *Tectonophysics,* 25, 41-67.

PEARCE J. A. (1975) Role of the sub-continental lithosphere in magma genesis at active continental margins. In: *Continental Basalts and Mantle Xenoliths.* (Editors: Hawkesworth, C. J. and Norry, M. J.). 230-249. Shiva, Nantwich.

PEARCE J. A. and CANN J. R. (1973) Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth and Planetary Science Letters, 12, 339-349.

PEARCE J. A. and NORRY M. J. (1979) Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks. Contributions to Mineralogy and Petrology, 69, 33-47.

PÉREZ H. O. (1990) Sansahuin y Quimsacocha: centros de emisión de la Formación Tarqui. *Boletín Geológico Ecuatoriano,* Vol. 1, 69-73.

PRATT W. T., FIGUEROA J. and FLORES B. (1997) Geology of the Western Cordillera of Ecuador between 3-4°S. CODIGEM-BGS, Quito, Ecuador.

RIVERA M., EGÜEZ A. and BEATE B. C. (1992) El volcanismo Neógeno de los Andes Australes: Sus manifestaciones en la zona entre Cuenca y Soldados, Ecuador. Memorias de las Segundas Jornadas en Ciencias de la Tierra, p. 56-57.

SAUER W. (1957) *El mapa geológico del Ecuador. Memoria explicativa.* (Universidad Central; Quito).

SAUER W. (1965) *Geología del Ecuador.* Edit. Ministerio de Educación Pública, (Quito), 383 p.

SHERVAIS J. W. (1982) Ti-V plots and the petrogenesis of modern ophiolitic lavas. *Earth and Planetary Science Letters,* 59, 101-118.

SILLITOE R. H. (1974) Tectonic segmentation of the Andes: implications for magmatism and metallogeny. *Nature,* 250, 542-545.

SNELLING N. J. (1969) Personal communication in Bristow C. R. and Hoffstetter R. (1977) (Compilers). Lexique Stratigraphique International; Ecuador. Second Edition, Paris: Centre National de la Recherche Scientifique.

STEINMANN M. (1997a) Fission track age determinations of zircons for Misión Geológica Británica, Quito, Ecuador. Geological Institute ETH Zürich, Switzerland.

STEINMANN M. (1997b) The Cuenca Basin of southern Ecuador: tectono-sedimentary history and the Tertiary Andean evolution. Unpublished PhD thesis. Institute of Geology, ETH Zürich, Switzerland.

THALMANN H. E. (1946) Micropalaeontology of Upper Cretaceous and Paleocene in Western Ecuador. *Bulletin of the American Association of Petroleum Geologists,* Vol. 30, 345.

TSCHOPP H. J. (1948) Geologische Skizze von Ekuador. *Bull. Assoc. Suisse Géol. Ing. Pét.,* Vol. 15, 14-45.

TSCHOPP H. J. (1953) Oil explorations in the Oriente of Ecuador. 1938-1950. *Bulletin of the American Association of Petroleum Geologists,* Vol. 37, 2303-2347.

TROUW R. (1976) Cuatro cortes por la faja metamórfica de la Cordillera Real, Ecuador. Escuela Politécnica Litoral, Guayaquil.

UNITED NATIONS DEVELOPMENT PROGRAMME (1969) Survey of metallic and non-metallic minerals. Coal Investigations (Operation No. 1, Cuenca-Biblián and Loja). *Technical Report, United Nations Development Programme, Quito-New York.*

UNITED NATIONS DEVELOPMENT PROGRAMME (1969) Survey of metallic and non-metallic minerals. Geochemical exploration 1965-1969. *Technical Report No. 1. United Nations Development Programme,* Quito-New York.

UNITED NATIONS DEVELOPMENT PROGRAMME (1972) Survey of metallic and non-metallic minerals. *Technical Report No. 16. United Nations Development Programme,* Quito-New York.

VAN THOURNOUT F. (1991) Stratigraphy, magmatism and tectonism in the Ecuadorian Northwestern Cordillera, metallogenic and geodynamic implications. Unpublished PhD thesis, Katholieke Universiteit, Leuven.

VAN THOURNOUT F., AND GUZMÁN J. (1988) Brechas hidrotermales relacionadas con posibles centros eruptivos en los volcánicos Tarqui cerca de Angas, Azuay. Significado metalogénico para la Formación. Politécnica, Monografía de Geología 6. Vol. 13, No. 3, 7-31.

WALKER G. P. L. (1973) Lengths of lava flows. *Philosophical Transactions of the Royal Society of London,* 274, 107-118.

WILKINSON I. P. (1996) Foraminifera from a suite of slides from the Western Cordillera of the Ecuadorian Andes. Technical Report WH/96/99R. Biostratigraphy and Sedimentology Research Group BGS, Nottingham, United Kingdom.

WILKINSON I. P. (1997) Foraminifera from a suite of six samples from Ecuador. BGS open-file report WH97/85R.

WILLIAMS T. M., GAIBOR A. and DUNKLEY P. N. (1998) Geochemical reconnaissance survey of the Cordillera Occidental of Ecuador between 2°-3° S. Proyecto de Desarrollo Minero y Control Ambiental: Programa de Información Cartográfica y Geológica. Report No. 7.

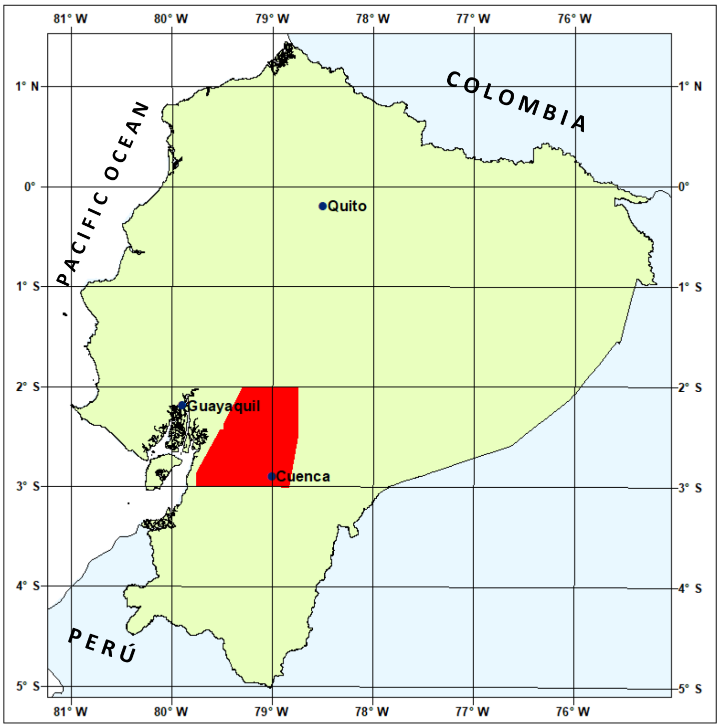
WINTER T. and LAVENU A. (1989) Morphological and microtectonic evidence for a major active right-lateral strike-slip fault across central Ecuador (South America). *Ann. Tectonicae,* 2, 123-129.

WOLF T. (1892) Geografía y Geología del Ecuador. Leipzig: Brockhaus.

APPENDIX 1 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 2°00’ AND 3°00’ S

GAMMA RADIATION



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 2 AREA)

QUITO, 1997

The use of Gamma-ray spectrometer readings for determination of rock compositions in the field

Gamma-ray spectrometer readings were taken at most outcrops examined during the second year of the project using a portable EDA instrument. These proved to be a valuable aid to evaluating rock compositions.

The instrument measured gamma-ray counts for five channels, including two channels for total gamma radiation of different energy levels, and three channels specifically for uranium, thorium and potassium.

A suite of tuffs from the Grupo Saraguro were analysed chemically and good linear correlations were found to exist between the intensity of gamma radiation and SiO_2 and K_2O contents. It was therefore possible to use gamma-ray measurements in the field to obtain fairly reliable estimates of tuff compositions. The general relationship of increasing gamma radiation with increasing SiO_2 and K_2O also held for the lavas of the area but was less clear. Examples of the calibrations obtained between the intensity of gamma radiation and SiO_2 and K_2O are illustrated in Figures A1 and A2 on the following pages.

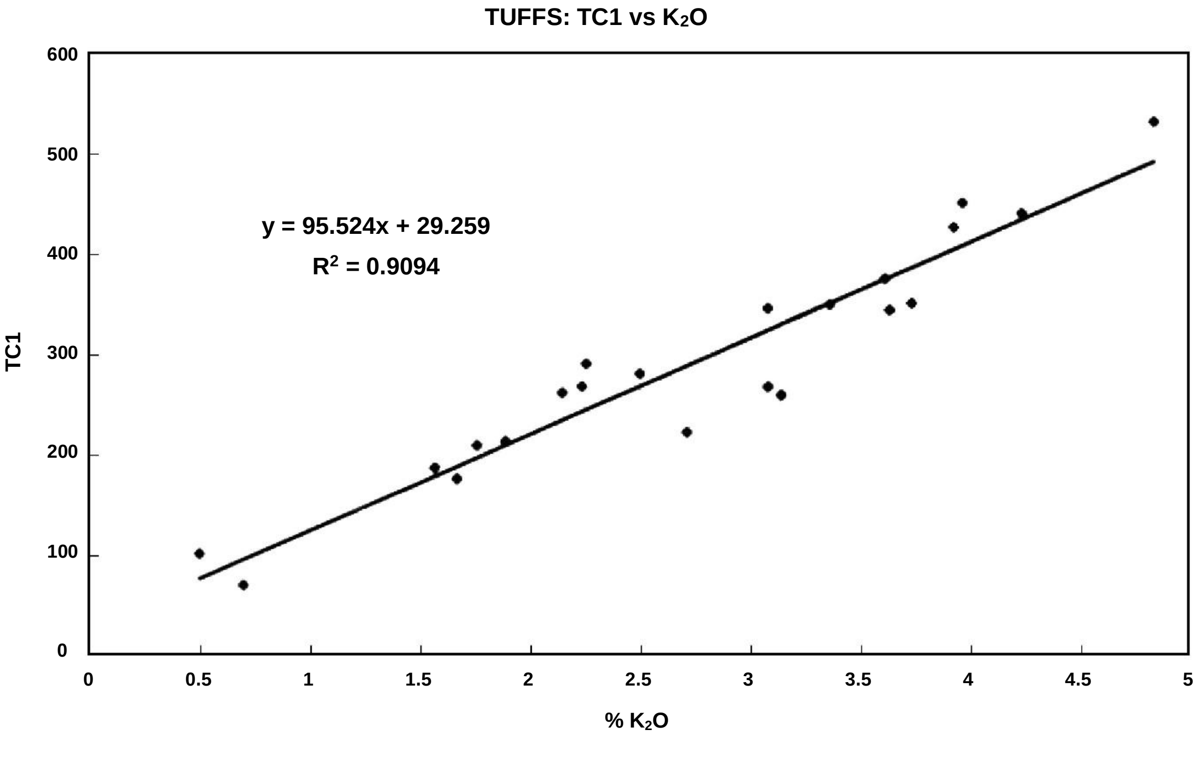


Figure A1. Relationship between Gamma radiation (Total counts – TC1) and K_2O for tuffs from the Grupo Saraguro

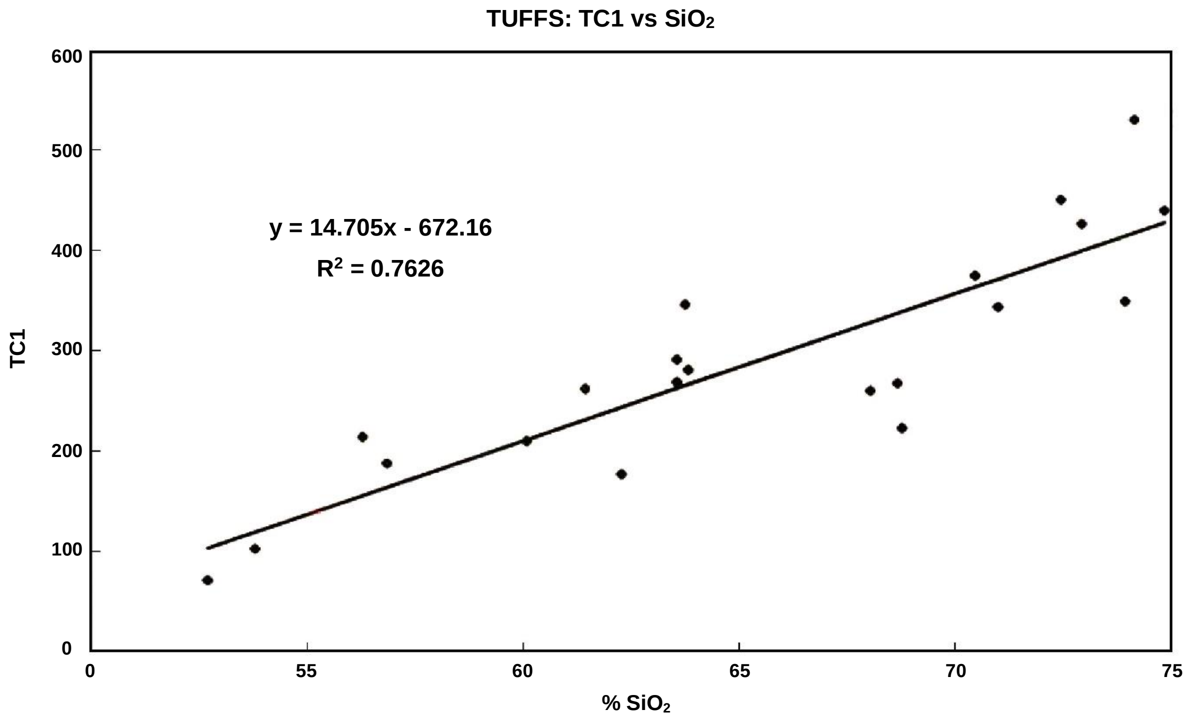
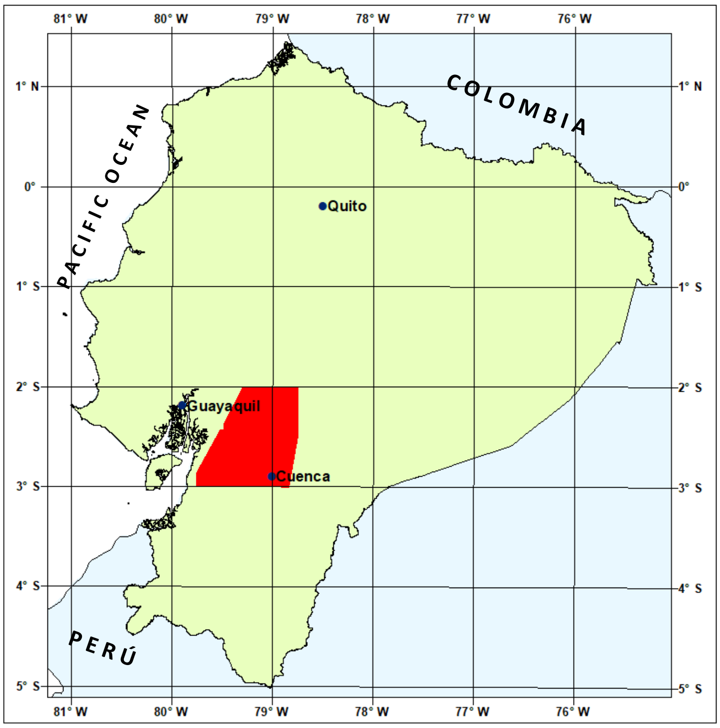


Figure A2. Relationship between Gamma radiation (Total counts – TC1) and SiO_2 for tuffs from the Grupo Saraguro

APPENDIX 2 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 2°00’ AND 3°00’ S

GEOCHEMICAL DATA DETAILS



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 2 AREA)

QUITO, 1997

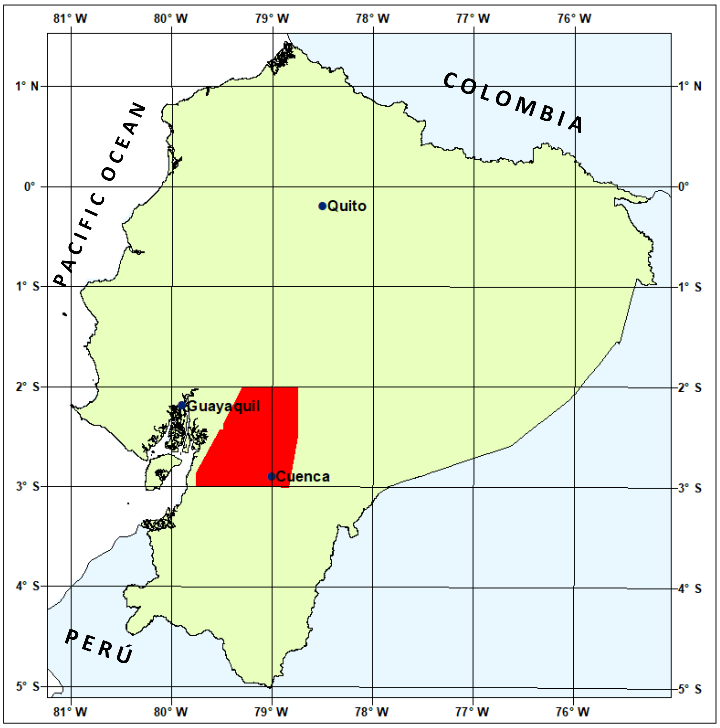
Table 1. Details of chemically analysed rock samples

Sample No.	UTMX	UTMY	Topographic map	Rock type	Lithostratigraphic unit
PND-50	68650	968995	S. F. de Molleturo	Andesitic tuff	Río Blanco Fm.
PND-168	69020	968000	Chaucha	Dacitic crystal ash-flow tuff	Soldados Fm.
PND-169	69060	967970	Chaucha	Dacitic crystal ash-flow tuff	Soldados Fm.
PND-196	72490	976490	Tixán	Basalt lava	Pallatanga Unit
PND-198	72550	976530	Tixán	Basalt lava	Pallatanga Unit
PND-199	72590	976540	Tixán	Basalt lava	Pallatanga Unit
PND-208	72650	975570	Alausí	Basalt lava	Pallatanga Unit
PND-224	71430	974410	Cumandá	Basalt lava	Pallatanga Unit
PND-225	71490	974540	Cumandá	Basalt lava	Pallatanga Unit
PND-226	71170	974680	Cumandá	Basalt lava	Pallatanga Unit
PND-267	67320	970090	S. F. de Molleturo	Andesite lava	Río Blanco Fm.
PND-268	67690	969850	S. F. de Molleturo	Andesite lava	Río Blanco Fm.
PND-270	67680	969700	S. F. de Molleturo	Andesite lava	Río Blanco Fm.
PND-271	67780	969520	S. F. de Molleturo	Andesite lava	Río Blanco Fm.
PND-272	70000	969180	Chiquintad	Andesitic ash-flow tuff	Tomebamba Unit
PND-273	70040	969210	Chiquintad	Dacitic ash-flow tuff	Tomebamba Unit
PND-274	70231	969333	Chiquintad	Intermediate ash-flow tuff	Tomebamba Unit
PND-339	74600	974560	Alausí	Andesite lava	Cisarán Fm.
PND-356	69740	972570	Suscal	Dacitic ash-flow tuff	Ocaña Fm.
PND-359	71640	974280	Cumandá	Dacitic ash-flow tuff	Ocaña Fm.
PND-905	68290	971570	Pancho Negro	Basalt lava	Pallatanga Unit
PND-994	71450	971820	S. F. de Gualleturo	Rhyolitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1015	72140	971760	S. F. de Gualleturo	Rhyolitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1017	72160	971930	S. F. de Gualleturo	Rhyolitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1019	72280	971200	Cañar	Dacitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1028	72580	971770	Cañar	Rhyolitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1035	72170	971750	S. F. de Gualleturo	Rhyolitic crystal ash-flow tuff	Cerro Caucay Fm.
PND-1047	72870	973070	Juncal	Dacite lava	Cisarán Fm.
PND-1079	74340	974350	Alausí	Dacite lava	Cisarán Fm.
PND-1081	74370	974330	Alausí	Andesite lava	Cisarán Fm.
PND-1168	69930	970150	Chiquintad	Andesite lava	Chanlud Fm.
PND-1192	72140	971230	S. F. de Gualleturo	Andesite lava	Chanlud Fm.
PND-1350	69850	970100	Chiquintad	Andesite lava	Chanlud Fm.
PND-1364	69699	970020	Chaucha	Dacite lava	Chanlud Fm.
PND-1370	96476	969640	Chiquintad	Andesite dyke	Chanlud Fm.
PND-1402	71495	969880	Chiquintad	Andesite lava	Chanlud Fm.
PND-1421	71310	970610	S. F. de Gualleturo	Dacite lava	Chanlud Fm.
PND-1436	68897	967110	Chaucha	Obsidian lapilli	Plancharumi Fm.
PND-1441	67060	970285	S. F. de Molleturo	Basalt lava	Pallatanga Unit
PND-1476	69065	972550	La Troncal	Basalt lava	Pallatanga Unit
PND-1482	70231	973317	Suscal	Basalt lava	Pallatanga Unit
PND-1508	66960	970120	S. F. de Molleturo	Basalt lava	Pallatanga Unit
PND-1616	68600	967086	Chaucha	Obsidian zone in rhyolite lava	Plancharumi Fm.
PND-1659	69743	971369	Gualleturo	Andesite lava	Chanlud Fm.
PND-1834	68565	968650	Chaucha	Altered andesite lava	Río Blanco Fm.
PND-1835	68550	968645	Chaucha	Intermediate crystal lithic tuff	Río Blanco Fm.
PND-1907	69170	969460	S. F. de Molleturo	Andesite lava	Chanlud Fm.
PND-2125	69486	968687	S. F. de Molleturo	Rhyolite lava	Chanlud Fm.
PND-2165	67857	968988	S. F. de Molleturo	Intermediate lava	Río Blanco Fm.

APPENDIX 3 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 2°00' AND 3°00' S

PETROGRAPHY



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 2 AREA)

QUITO, 1997

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-4	Chaucha	67920	967900	Acid lava (hornfelsed?)	Fine grained flow-banded acid lava. Recrystallized	
PND-5	Chaucha	67930	967900	Acid lava (hornfelsed?)	Fine grained flow-banded acid lava. Recrystallized	
PND-7	Chaucha	68360	967850	Dacitic lapilli tuff	Crystals of plag, embayed quartz, minor biotite and amphibole. Lapilli of andesite lava	Plag, qtz, bt, amph
PND-9	Chiquintad	70370	969200	Andesitic lava	Microporphyritic. Microphenocrysts of plag in fine matrix composed of feldspar laths. Secondary chlorite and epidote	Plag, feld, chl, epid
PND-11	Chiquintad	70340	969200	Andesitic lava	Altered. Microporphyritic. Microphenocrysts of plag plus chloritised pyroxene and amphibole and traces of biotite. Groundmass finely recrystallised	Plag, px, amph, chl, bt
PND-17	Chiquintad	70090	969230	Andesitic tuff	Strongly welded brown glassy matrix with flattened pumice. Crystals of plag plus pyroxene and other chloritised mafic crystals	Plag, px, chl
PND-19	Chiquintad	69750	969260	Rhyolite	Recrystallized mosaic of quartz and feldspar	Qtz, feld
PND-21	S. F. Molleturo	67790	969540	Andesitic lava	Altered. Microporphyritic. Abundant plagioclase. Mafic crystals altered to chlorite and epidote. Veinlets of chlorite. Finely recrystallized groundmass	Plag, chl, epid
PND-22	S. F. Molleturo	67790	969540	Andesitic lava	Altered. Microporphyritic. Plagioclase altered to epidote and quartz. Mafic phenocrysts completely altered to chlorite. Matrix fine and recrystallized	Epid, qtz, chl
PND-24	Chiquintad	69500	969360	Rhyolitic vitric tuff	Very fine rhyolitic sediment/vitric tuff (dust tuff?)	
PND-26	S. F. Molleturo	69400	969370	Dacitic/Rhyolitic lapilli tuff	Crystals of quartz, feldspar and lithic clasts in strongly welded glassy matrix. Sericitised	Qtz, feld
PND-29	S. F. Molleturo	67670	969600	Andesitic tuff/hyaloclastite	Altered. Coarse glass shards replaced by chlorite, sericite and quartz. Crystals of feldspar and mafic minerals altered to sericite, chlorite and calcite	Chl, seric, qtz, feld, chl, calc
PND-30	Suscal	69930	972800	Dacitic tuff	Strongly welded brown glassy matrix with eutaxitic fabric. Crystal rich with abundant plag, numerous rounded quartz crystals, hornblende and traces of biotite. Chlorite after biotite?	Plag, qtz, hbl, bt, chl
PND-33	Cuenca	70900	972480	Andesitic tuff	Crystal rich with plagioclase chloritised cpx? and amphibole crystals in welded glassy matrix	Plag, cpx, amph
PND-34	Chiquintad	70550	968600	Andesitic tuff	Strongly welded and crystal rich. Sericitised plagioclase crystals and minor amounts of chloritised mafic minerals. Lithic lapilli. Pale brown recrystallised glass with abundant fiamme	Plag, chl
PND-35	Chiquintad	69970	969200	Andesitic/Dacitic tuff	Crystal rich, welded. Crystals of plag, embayed irregular quartz, chloritised mafics including pseudomorphs after hornblende. Lithic lapilli of another welded tuff	Plag, qtz, chl, hbl
PND-36	Chiquintad	69740	969270	Rhyolite	Recrystallized acid volcanic rock. No obvious original fabric. Sparsely feldsparphyric	Feld
PND-37	Chiquintad	69590	969320	Dacitic lapilli tuff	Crystal and lapilli-rich. Crystals of plag and quartz in equal proportions, some chlorite pseudomorphs after mafics. Fiamme. Strongly welded	Plag, qtz, chl
PND-40	Chiquintad	69520	969480	Vitroclastic rhyolite tuff	Composed of recrystallized very fine delicate shards replaced by quartz and feldspar. Diffuse zones rich in carbon. Probably reworked secondary tuff?	Qtz, feld
PND-43	Chiquintad	69470	969310	Rhyolitic tuff	Strongly recrystallized but vitroclastic and eutaxitic fabric evident. Looks weakly welded	
PND-44	Chiquintad	69460	969300	Rhyolitic tuff	Intensely welded with very strong eutaxitic fabric. Crystals of plagioclase and quartz and lithic lapilli	Plag, qtz
PND-45	S. F. Molleturo	69390	969350	Dacitic tuff	Welded crystals of sericitised plag, minor quartz and lithic lapilli. Very finely recrystallized groundmass with fiamme	Plag, qtz
PND-71	S. F. Molleturo	67240	970060	Basaltic andesite/andesite lava	Altered. Microphenocrysts of plagioclase and pseudomorphs of chlorite, actinolite and epidote after a mafic mineral, set in a fine feldspathic groundmass	Plag, chl, actl, epid, feld
PND-73	S. F. Molleturo	67180	970110	Andesitic lava	Altered. Pseudomorphs after feldspar and amphibole in a fine feldspathic matrix	Fled, amph
PND-74	S. F. Molleturo	67110	970090	Hornblende andesitic lava	Subhedral-anhedral microphenocrysts of green amphibole up to 2.5 mm in a fine feldspathic matrix	Amph, feld
PND-76	S. F. Molleturo	67020	970210	Altered sediment	Fine chloritic and epidote rich sediment. Siltstone grade. Looks like a flamed and mixed sediment, but could be sheared. Slight possibility this rock is a sheared basalt	Chl, epid
PND-79	S. F. Molleturo	67310	970100	Basaltic andesite/basalt	Microphenocrysts of cpx, plag and minor opx	Cpx, plag, opx
PND-81	S. F. Molleturo	66980	970230	Sheared basalt	Remnant areas with subophitic fabric (cpx + plag) in a cataclastic matrix	Cpx, plag
PND-82	S. F. Molleturo	67060	970300	Sheared basalt	Altered, rich in actinolite, chlorite and epidote. Cataclastic texture consisting of areas or clasts of subophitic basalt and cpx with granulated margins/trails in a finer sheared matrix. Sheared fabric is crenulated with good S/C type structures	Actl, chl, epid, cpx

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-85	Pancho Negro	67230	970610	Sheared basalt	Altered rich in chlorite, actinolite, epidote and calcite. Cataclastic texture with granulated and fracture clinopyroxene in a finer sheared matrix	Chl, actl, epid, calc, cpx
PND-88	Pancho Negro	67300	970620	Sheared basalt/microgabbro	Areas of clasts of subophitic cpx and plg, moderately coarse (for this reason could be a microgabbro or lava), set in a sheared matrix rich in chlorite and zeolites	Cpx, plag, chl, zeol
PND-93	Suscal	70410	972800	Andesite lava	Microphenocrysts of plagioclase, magnetite and anhedral/resorbed amphibole, set in a brown glassy matrix with feldspar microlite and magnetite. In places fresh in others altered with carbonate	Plag, mag, amph, feld, carbt
PND-94	Suscal	70100	972640	Dacitic/andesitic crystal-tuff	Strongly welded crystal tuff. Crystals of plag, amphibole, magnetite and rounded quartz, set in a brown glassy matrix with flattened pumice and shards. Some lithic clasts of siltstone	Plag, amph, mag, qtz
PND-96	La Troncal	69030	972490	Basalt	Aphyric. Good variolitic texture with sheaf-like, curved acicular crystals of plag intergrown with cpx. Rare microphenocrysts of plagioclase and cpx 1 to 1.5 mm in a very fine matrix	Plag, cpx
PND-97	La Troncal	69080	972670	Basalt	Fine grained with variolitic texture	
PND-99	Juncal	72870	973130	Two-pyroxene andesite	Microphenocrysts of plagioclase, cpx and opx in fine matrix	Plag, cpx, opx
PND-100	Juncal	72860	973060	Andesite lava	Microphenocrysts of cpx, plag, pale green amphibole and magnetite in a pilotaxitic matrix of feldspar laths and microlites	Cpx, plag, amph, mag, feld
PND-101	Juncal	73170	973120	Hornblende andesite lava	Microporphyritic. Complexly zoned plagioclase and euhedral-subhedral pseudomorphs of finely divided oxide after amphibole	Plag, amph
PND-105	La Troncal	69070	973300	Basaltic microbreccia	Altered, chloritised and carbonated. Polymict clasts of fine basalt (vesicular) and chloritised shards in a very fine chloritised glass matrix	Chl, carbt
PND-107	La Troncal	69080	973280	Basalt	Very fine amygdaloidal, chloritised basalt lava. Originally glassy	Chl
PND-109	La Troncal	69150	973590	Basalt	Fine grained, aphyric variolitic basalt. Chloritised. Fine amygdales of chlorite and zeolite	Chl, zeol
PND-110	Cumandá	70370	974580	Basalt	Altered, medium-grained with chlorite, epidote and zeolites	Chl, epid, zeol
PND-112	Cumandá	70730	974800	Basalt	Altered, microporphyritic. Microphenocrysts of plag in a very fine feldspathic, pilotaxitic matrix	Plag, feld
PND-113	Cumandá	70960	974860	Basalt	Medium-fine grained sub-ophitic basalt. Intergrown/interlocking plagioclase and cpx, with interstitial glass with feldspar microlites and chlorite	Plag, cpx, chl
PND-114	Cumandá	71070	974730	Basalt	Altered. Very fine chloritised lava. With veins and amygdales of chlorite, zeolite and calcite	Chl, zeol, calc
PND-121	Cumandá	71630	974330	Dacitic tuff	Crystal rich weakly welded. Numerous plag crystals, large embayed quartz crystals and minor hornblende. Recrystallised matrix	Plag, qtz, hbl
PND-122	Cumandá	71660	974260	Two-pyroxene andesite lava	Glassy, very finely recrystallised flow-banded groundmass. Numerous phenocrysts of strongly zoned plag, cpx, opx and magnetite	Plag, cpx, opx, mag
PND-126	Cumandá	71930	974290			
PND-127	Cumandá	71960	974310	Andesite lava	Microporphyritic with phenocrysts of plag and minor mafics replaced by chlorite and calcite. Groundmass of plagioclase laths	Plag, chl, calc
PND-128	Cumandá	71980	974350	Hornblende andesite lava	Chloritised. Microphenocrysts of plagioclase, hornblende and magnetite, plus chlorite pseudomorphs after a mafic mineral	Plag, hbl, mag, chl
PND-131	Cumandá	72170	974330	Dacitic lapilli tuff	Very crystal rich lapilli tuff. Numerous crystals of plagioclase, fresh hornblendes and rounded quartz. Lithic lapilli	Plag, hbl, qtz
PND-134	Alausí	72320	974570	Andesite lava	Microporphyritic. Microphenocrysts of plag and minor cpx in a pilotaxitic matrix	Plag, cpx
PND-153	Chaucha	68060	968040	Altered tuff	Secondary? Chloritised. Intermediate to acid composition	Chl
PND-161	Chaucha	68310	967810	Rhyolitic tuff	Strongly welded acid tuff with rhyolitic lithic lapilli and crystals of feldspar	Feld
PND-166	Chaucha	68650	968000	Tonalite/quartz-diorite	Medium-coarse grained. Interlocking crystals of plagioclase (andesine-oligoclase), minor mafic phenocrysts altered to actinolite, magnetite and much intergranular quartz and feldspar	Plag, actl, mag, qtz, feld
PND-170	Chaucha	69080	967930	Dacitic/rhyolitic tuff	Welded with intense eutaxitic fabric. Numerous partly altered plagioclase crystals, abundant subhedral-anhedral quartz crystals (rounded and embayed). Minor mafic crystals altered to chlorite and epidote. Brown glassy groundmass	Plag, qtz, chl, epid
PND-171	Chaucha	69050	977920	Dacitic/andesitic lapilli tuff	Welded. Crystal tuff. Numerous feldspar crystals and numerous embayed quartz crystals	Feld, qtz
PND-173	Chaucha	69330	967920	Dacitic tuff	Welded crystal tuff with numerous embayed quartz crystals	Qtz

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-178	S. F. Molleturo	68120	969150	Andesitic tuff	Welded andesitic tuff. Numerous plagioclase phenocrysts, minor magnetite. Shard-like clasts replaced by chlorite	Plag, mag, chl
PND-186	Tixán	73320	977040	Two-pyroxene andesite lava	Microphenocrysts of plag, cpx, minor opx and magnetite in a feldspathic groundmass	Plag, cpx, opx, mag, feld
PND-187	Tixán	73320	977090	Andesite lava	Same rock as PND-186 but altered. Plagioclase and phenocrysts altered to calcite, quartz and chlorite. Feldspathic groundmass. Veinlets of calcite and quartz	Plag, calc, qtz, chl, feld
PND-196	Tixán	72490	976490	Basalt lava	Fine grained variolitic basalt with sheet like aggregates of curved acicular plagioclase intergrown with clinopyroxene (i.e. quench texture). Glassy chloritic matrix	Plag, cpx, chl
PND-198	Tixán	72550	976530	Basalt lava	Medium to fine grained, fresh basalt with subophitic/variolitic textures. Intergrown cpx and plagioclase, intergranular magnetite/titanomagnetite. Glassy interstices with microlites altered to chlorite	Cpx, plag, mag, titmag, chl
PND-199	Tixán	72590	976540	Basalt lava	Variolitic basalt with good quench textures. Intergrown cpx and plag with interstitial chlorite (after glass)	Cpx, plag, chl
PND-204	Alausí	72840	975450	Andesite lava	Altered. Very fine grained microporphyritic. Microphenocrysts of plag (up to 1 mm)	Plag
PND-205	Alausí	72830	975490	Andesite lava	Microbrecciated and microporphyritic with microphenocrysts of plagioclase, plus euhedral-subhedral cpx and minor amphibole. Very fine microlithic matrix.	Plag, cpx, amph
PND-206	Alausí	72600	975400	Andesite tuff	Crystal rich with broken crystals of plag, chloritised mafics, minor hornblende in very fine recrystallised matrix (could possibly be a lava)	Plag, chl, hbl
PND-207	Alausí	72570	975440	Andesite lava	Altered. Microphenocrysts of plag, chlorite and epidote in fine pilotaxitic matrix	Plag, chl, epid
PND-208	Alausí	72650	975570	Basalt lava	Subophitic-granular texture. Fresch cpx, granular and intergrown with sericitised plag, magnetite and interstitial chlorite	Cpx, plag, seric, mag, chl
PND-209	Alausí	72660	975570	Basaltic hyaloclastite	Altered. Clasts of altered very fine-grained basalt, and large chloritised glass shards formed by quenching	Chl
PND-211	Alausí	72660	975570	Andesitic tuff	Crystal rich, probably secondary tuff. Crystals mainly of broken plag, minor quartz and minor hornblende, magnetite and lithic clasts of andesite lava	Plag, qtz, hbl, mag
PND-213	Alausí	72700	974880	Andesite lava	Microporphyritic. Numerous complexly zoned plag phenocrysts, hornblende in very fine matrix	Plag, hbl
PND-214	Alausí	72800	974950	Andesite microbreccia	Clasts of andesite lava and crystals in a matrix of poorly sorted immature sandstone	
PND-224	Cumandá	71430	974410	Basalt	Variolitic. Good quench texture composed of cpx intergrown with curved acicular plagioclase in places subophitic texture. Interstitial chlorite. Minor calcite veinlets	Cpx, plag, chl, calc
PND-225	Cumandá	71490	974540	Basalt	Very fine grained variolitic aphyric basalt. Cpx intergrown with skeletal plagioclase with interstitial glass/chlorite	Cpx, plag, chl
PND-226	Cumandá	71170	974680	Basalt	Very fine grained variolitic aphyric basalt. Cpx intergrown with skeletal plagioclase with interstitial glass/chlorite	Cpx, plag, chl
PND-232	Cuenca	70350	967460	Dacitic tuff	Intensely welded lapilli tuff with clasts of andesite lava, scoria and sediments. Tubular pumice lapilli. Numerous crystals of feldspar and abundant embayed quartz crystals	Feld, qtz
PND-235	Cuenca	69480	967740	Dacitic? tuff	Crystal-rich lapilli tuff. Numerous feldspar crystals, embayed crystals of quartz, minor magnetite and amphibole, lithic lapilli. Welded	Feld, qtz, mag, amph
PND-236	Cuenca	69490	967750	Dacitic? tuff	Crystal-rich lapilli tuff. Numerous feldspar crystals, embayed crystals of quartz, minor magnetite and amphibole, lithic lapilli. Welded	Feld, qtz, mag, amph
PND-243	Cuenca	70050	967530	Dacitic? tuff	Crystal-rich lapilli tuff. Numerous feldspar crystals, embayed crystals of quartz, minor magnetite and amphibole, lithic lapilli. Brown glassy welded matrix	Feld, qtz, mag, amph
PND-247	Cuenca	69990	967480	Rhyolitic tuff	Pale pink-white vitroclastic tuff. Minor crystals of quartz and feldspar, lithic lapilli and pumice lapilli including tubular pumice	Qtz, feld
PND-248	Cuenca	69990	967470	Rhyolitic tuff	Red vitroclastic tuff. Vesicular matrix of shards and pumice	
PND-252	Chiquintad	69570	969570	Andesitic tuff	Welded lapilli tuff. Tubular pumice and lithic lapilli of dacitic lava. Numerous feldspar crystals but no quartz	Feld
PND-253	Chiquintad	69570	969570	Rhyolitic tuff	Recrystallized. Numerous fractured quartz crystals, biotite crystals	Qtz, bt
PND-254	Chiquintad	69610	969590	Dacitic/Rhyolitic tuff	Welded crystal tuff. Numerous crystals of feldspar and biotite, and some embayed quartz crystals. Lithic lapilli	Feld, bt, qtz
PND-255	Chiquintad	69990	969130	Dacitic tuff	Welded crystal tuff. Crystals of feldspar, amphibole and numerous embayed and rounded quartz crystals	Feld, qtz
PND-267	S. F. Molleturo	67320	970090	Andesite lava	Two-pyroxene andesite. Microporphyritic. Microphenocrysts of plagioclase, cpx, minor pale-brown, clear pleochroic orthopyroxene (hypersthene), chlorite after mafic mineral, magnetite. Fine recrystallised matrix with snow-flake texture	Plag, cpx, opx, chl, mag

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-268	S. F. Molleturo	67690	969850	Andesite lava	Two-pyroxene andesite. Microporphyritic. Microphenocrysts of plag, cpx, altered opx (hypersthene) and magnetite. Chloritic finely recrystallised matrix	Plag, cpx, opx, mag, chl
PND-269	S. F. Molleturo	67450	970130	Andesite lava	Altered andesite autobrecciated lava/breccia. Pseudomorphs of magnetite after amphibole	Mag, amph
PND-270	S. F. Molleturo	67680	969700	Andesite lava	Microporphyritic. Microphenocrysts of plag, cpx and chloritised mafics in very fine matrix	Plag, cpx, chl
PND-271	S. F. Molleturo	67780	969520	Andesite lava	Altered, microporphyritic. Microphenocrysts of plagioclase and chloritised mafic minerals, in a fine recrystallized matrix with snow-flake texture. Much secondary chlorite and calcite	Plag, chl, calc
PND-272	Chiquintad	70000	969180	Andesitic tuff	Altered welded andesitic tuff. Feldspar crystals, chlorite after amphibole plus calcite	Feld, chl, amph, calc
PND-273	Chiquintad	70040	969210	Dacitic tuff	Altered welded dacitic tuff. Feldspar crystals, chlorite after amphibole, plus calcite	Feld, chl, amph, calc
PND-280	Chiquintad	71150	969910	Basaltic andesite/andesite lava	Altered, microporphyritic. Plagioclase, completely chloritised mafics. Fine matrix with chlorite and calcite	Plag, chl, calc
PND-287	Chiquintad	72070	970040	Andesite lava	Microporphyritic. Microphenocrysts of plag and less common chloritised mafic crystals in pilotaxitic matrix of plagioclase laths and microlites	Plag, chl
PND-288	Chiquintad	71970	970230	Andesite lava	Microporphyritic. Microphenocrysts of plag and less common chloritised mafic crystals in pilotaxitic matrix of plagioclase laths and microlites	Plag, chl
PND-290	Chiquintad	70020	969280	Andesitic/dacitic tuff	Altered welded tuff. Crystals of feldspar, chlorite pseudomorphs after amphibole, rare quartz crystals	Feld, chl, amph, qtz
PND-292	Chiquintad	70040	969450	Basalt/Basaltic andesite	Microporphyritic. Microphenocrysts of plag, cpx and partly chloritised pleochroic opx	Plag, cpx, chl, opx
PND-293	Chiquintad	70090	969440	Andesite tuff	Welded crystal tuff. Numerous plagioclase crystals, chlorite after mafic crystals set in a recrystallised groundmass with a eutaxitic fabric	Plag, chl
PND-295	Chiquintad	70140	969380	Andesite clast	Clast of andesite lava. Phenocrysts of plagioclase and chloritised mafic minerals	Plag, chl
PND-296	Chiquintad	69650	969270			
PND-304	Cuenca	70640	968480	Andesite lava	Flow-banded. Microphenocrysts of plagioclase in a very fine groundmass with microlites. Partly recrystallized with snow-flake texture	Plag
PND-305	Cuenca	70660	968480	Andesite lava	Very fine-grained andesite lava. Altered. Microphenocrysts of plagioclase altered to calcite and chlorite after mafic microphenocrysts in a very fine pilotaxitic groundmass	Plag, calc, chl
PND-306	Cuenca	70630	968480	Andesite lava	Microporphyritic and partly altered. Microphenocrysts of plagioclase. Abundant mafic microphenocrysts completely altered to chlorite and calcite, minor fresh cpx. Microlithic matrix	Plag, chl, calc, cpx
PND-308	Cuenca	70630	968490	Andesite lava	Completely altered fine vesicular lava, chlorite and calcite. Rare microphenocrysts of plagioclase replaced by calcite	Chl, calc, plag
PND-311	Cuenca	70630	968510	Andesite lava	Sparsely microporphyritic. Microphenocrysts of plagioclase and mafics altered to chlorite and calcite in a fine pilotaxitic matrix	Plag, chl, calc
PND-324	Alausí	73270	974580	Andesite microbreccia	Hornblende andesite microbrecciated lava or microbreccia. Microphenocrysts of plag, hornblende, magnetite and rare embayed quartz crystals	Plag, hbl, mag, qtz
PND-326	Alausí	73280	974880	Andesite lava	Microporphyritic. Phenocrysts of plag, cpx and opx, resorbed and oxidised amphiboles	Plag, cpx, opx, amph
PND-327	Alausí	73360	974980	Andesite lava	Altered with microphenocrysts of amphibole	Amph
PND-328	Alausí	73510	975000	Basaltic andesite lava	Microporphyritic. Plagioclase (labradorite-andesite, not complexly zoned), much fresh cpx and chlorite pseudomorphs after amphibole. Set in a fine matrix of feldspar laths and microlites.	Plag, cpx, chl, amph, feld
PND-330	Alausí	74240	975250	Andesite lava	Altered. Carbonated and chloritised	Carbt, chl
PND-332	Alausí	74160	975780	Andesite lava	Microporphyritic. Phenocrysts of plagioclase, slightly pleochroic clinopyroxene, amphibole and magnetite in a fine feldspathic matrix with a pilotaxitic fabric	Plag, cpx, amph, mag, feld
PND-339	Alausí	74600	974560	Andesite lava	Very fine and sparsely microporphyritic. Small phenocrysts of cpx (>0.3 mm) and oxide pseudomorphs after amphibole, set in a pilotaxitic groundmass of plagioclase laths	Cpx, amph, plag
PND-345	Tixán	74480	976260	Andesite lava	Slightly altered. Microphenocrysts of plagioclase and green amphibole set in a very fine matrix	Plag, amph
PND-841	Cuenca	71160	967660	Andesite lava	Dark green microporphyritic lava. Flow-banded. Microporphyritic. Phenocrysts of plag, cpx, chloritised mafic (possibly amphibole) and magnetite. Pilotaxitic groundmass	Plag, cpx, chl, amph, mag
PND-843	Pijilí	66610	968040	Actinolite schist?	Alternating bands of actinolite and quartz-feldspathic bands. Sheared	Actl, qtz, feld

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-845	Chaucha	66850	967960	Rhyolitic/dacitic tuff	Welded acid tuff. Crystals of feldspar and quartz. Pumice lapilli-tubular pumice. Some chlorite and epidote	Feld, qtz, chl, epid
PND-848	Chaucha	66970	967930	Sheared sediment?	Possible secondary tuff/volcanic sandstone. Matrix of broken feldspars with interstitial chlorite and mafic crystals. Altered to actinolite and calcite with veinlets of zeolite	Feld, chl, actl, calc, zeol
PND-850	Pijilí	65960	967640	Sheared sediment	Altered sediment rich in actinolite and chlorite. Grains of feldspar, quartz and mafic minerals. Late stage fine acicular actinolite growing across the fabric	Actl, chl, feld, qtz
PND-851	Pijilí	66030	967520	Altered sediment	Altered and possibly sheared. Rich in chlorite and actinolite. Coarse mafic crystals altered to chlorite and actinolite, matrix of fine, banded silty mudstone with fine quartz grains	Chl, actl, qtz
PND-853	Pijilí	66140	967400	Sandstone	Immature quartz-rich dirty sandstone. Angular quartz clasts supported in a fine sericitic matrix	Qtz, seric
PND-854	Pijilí	66140	967330	Altered basic tuff	Altered basaltic tuff/microbreccia; possible hyaloclastite. Much chlorite, epidote and calcite. Chloritised shards and altered lava fragments	Chl, epid, calc
PND-871	Suscal	71300	973220	Microporphyritic diorite	Hornblende microdiorite. Phenocrysts of plagioclase, hornblende, magnetite and rare quartz, in a fine crystalline groundmass	Plag, hbl, mag, qtz
PND-873	Suscal	71270	973400	Diorite/andesite	Microporphyritic. Microphenocrysts of plagioclase, magnetite and magnetite after amphibole in a very fine groundmass with minor secondary silicification	Plag, mag, amph
PND-877	Suscal	70970	972780	Andesite clast	Strongly microporphyritic hornblende andesite	Hbl
PND-881	Suscal	71020	972720	Diorite	Abundant complexly zoned plagioclase microphenocrysts, chlorite pseudomorphs after cpx, in feldspathic matrix with minor interstitial quartz	Plag, chl, cpx, feld, qtz
PND-886	Suscal	71220	972430	Andesite/basaltic andesite	Altered andesite/basaltic andesite lava. Microporphyritic. Microphenocrysts of plag, pseudomorphs of calcite and chlorite possibly after amphibole and cpx	Plag, calc, chl, amph, cpx
PND-888	Suscal	71300	972380	Intermediate lapilli tuff	Strongly altered andesitic/dacitic lapilli tuff with fiamme. Much chlorite, calcite and pyrite	Chl, calc, py
PND-889	Suscal	71320	972360	Intermediate lapilli tuff	Welded dacitic/andesitic tuff with fiamme and numerous lithic lapilli. Crystals of feldspar, rare quartz crystals. Chlorite and epidote	Feld, qtz, chl, epid
PND-892	Gualleturo	71100	972300	Andesite lava (altered)	Altered andesite lava. Microphenocrysts of plagioclase in fine pilotaxitic groundmass. Much chlorite, calcite, epidote and quartz	Chl, calc, epid, qtz
PND-902	Gualleturo	70160	972310	Andesite lava clast	Clast from breccia of altered andesite lava	
PND-903	Gualleturo	70120	972300	Acid crystal tuff	Welded dacitic crystal tuff. Feldspar crystals set in a brown glassy matrix which is recrystallised with snow-flake texture. Eutaxitic fabric	Feld
PND-905	Pancho Negro	68290	971570	Variolitic basalt	Very fine-grained variolitic basalt with sporadic clasts of chloritised glass	Chl
PND-909	Pancho Negro	68460	971570	Variolitic basalt	Very fine-grained variolitic basalt	
PND-910	Pancho Negro	68490	971590	Variolitic basalt	Very fine-grained variolitic basalt	
PND-917	Pancho Negro	67760	971420	Basaltic sandstone	Altered basic volcanic sandstone. Wacke texture – crystals and lithic clasts supported in a fine matrix. Altered with much chlorite and calcite	Chl, calc
PND-918	Pancho Negro	67780	971390	Basaltic tuffaceous sandstone	Altered with much calcite. Angular grains of feldspar, quartz and possible lithic clasts. Numerous chloritised (penninite) glass shards	Calc, feld, qtz
PND-922	Pancho Negro	67860	971280	Volcanic sandstone	Feldspathic wacke sandstone with much chlorite	Feld, chl
PND-923	Pancho Negro	67870	971240	Volcanic sandstone	Dirty volcanic sandstone. Crystals of plagioclase, cpx and chlorite possibly after glass	Plag, cpx, chl
PND-932	Juncal	72260	973860	Andesite microbreccia	Hornblende andesite microbreccia. Predominantly composed of clasts of hornblende andesite, with broken feldspar and quartz crystals in the interstices	Hbl, feld, qtz
PND-934	Suscal	72240	974090	Basaltic andesite lava	Microporphyritic. Phenocrysts of plagioclase, cpx, altered amphibole and magnetite	Plag, cpx, amph, mag
PND-937	Pijilí	66220	967150	Altered basic sediment?	Clastic rock extensively altered to chlorite, epidote and actinolite. Maybe a basic tuff originally	Chl, epid, actl
PND-938	Pancho Negro	61000	970100	Basalt lava	Very fine-grained variolitic basalt with minor amounts of epidote, chlorite and quartz in fine veinlets	Epid, chl, qtz
PND-939	Pijilí	66030	967070	Basalt	Very fine basalt lava with quench textures. Very fine variolitic texture with microphenocrysts of plagioclase with hollow centres. Veinlets of actinolite, some chlorite	Plag, actl, chl
PND-951	Chaucha	67090	967860	Actinolite-rich rock	Actinolite with interlocking laths of plagioclase and minor magnetite. Could be an altered basalt	Actl, plag, mag

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-982	Chiquintad	69940	969330	Intermediate tuff	Welded andesitic/dacitic crystal tuff. Numerous feldspar crystals, calcite-chlorite pseudomorphs after mafic crystals, some magnetite crystals. Recrystallized fine brown glassy matrix with fiamme and shards	Feld, calc, chl, mag
PND-986	Gualleturo	70850	971740	Andesite lava	Microporphyritic andesite lava. Euhedral-subhedral plagioclase, mafic phenocrysts altered to chlorite and calcite. Some fresh cpx and magnetite in a fine pilotaxitic, feldspathic matrix	Plag, chl, calc, cpx, mag, feld
PND-988	Gualleturo	71040	971700	Andesite lava	Microporphyritic andesite lava. Euhedral-subhedral plagioclase, mafic phenocrysts altered to chlorite and calcite. Some fresh cpx and magnetite in a fine pilotaxitic, feldspathic matrix	Plag, chl, calc, cpx, mag, feld
PND-993	Gualleturo	71400	971800	Dacitic lava	Altered acid lava. Microphenocrysts of feldspar altered to calcite. Chlorite after mafics and amphibole altered to magnetite, minor small quartz phenocrysts, set in a pilotaxitic matrix of feldspar laths	Feld, calc, chl, amph, mag, qtz, feld
PND-994	Gualleturo	71450	971820	Rhyolitic crystal tuff	Strongly welded rhyolitic tuff. Crystals of feldspar, embayed quartz, minor biotite partly altered to chlorite, possible chlorite pseudomorphs after amphiboles, and minor magnetite. Very fine glassy matrix-sericitic with strongly welded fabric	Feld, qtz, bt, chl, amph, mag, seric
PND-995	Gualleturo	71480	971840	Andesite lava	Altered andesite lava with much chlorite and calcite. Feldspar microphenocrysts (altered to calcite). Fine altered matrix with calcite amygdales	Chl, calc, feld
PND-1004	Gualleturo	71750	971860	Andesite lava	Altered andesite lava. Microphenocrysts of plagioclase, partly altered to calcite, chloritised mafic microphenocrysts and magnetite in a fine calcite-rich matrix	Plag, calc, chl, mag
PND-1007	Gualleturo	71920	971700	Rhyolitic crystal tuff	Red-brown oxidised glassy tuff with excellent vitroclastic textures. Matrix consists of shards and pumice lapilli with broken crystals of feldspar and numerous embayed quartz crystals	Feld, qtz
PND-1008	Gualleturo	71960	971690	Andesite lava	Altered andesite-basaltic andesite lava. Microporphyritic with numerous plagioclase phenocrysts, chloritised mafic phenocrysts and possible pseudomorphs after olivine. Matrix of fine plagioclase laths with pilotaxitic fabric	Plag, chl, olv
PND-1013	Gualleturo	72090	971680	Andesite lava	Altered andesite lava. Much carbonate. Sporadic microphenocrysts of plagioclase in a fine groundmass composed of plagioclase laths and microlites	Carbt, plag
PND-1025	Cañar	72490	971940	Rhyolitic crystal tuff	Red-brown oxidised vitroclastic tuff. Feldspar crystals, numerous embayed crystals of quartz, much biotite, and hornblende. Some lithic clasts. Vitroclastic matrix composed of shards and pumice	Feld, qtz, bt, hbl
PND-1083	Alausí	74290	974410	Hornblende andesite lava	Microporphyritic. Complexly zoned plagioclase, numerous hornblende microphenocrysts with oxidised rims. Fine matrix of plagioclase laths and microlites	Plag, hbl
PND-1101	Naranjal	65460	969610	Hornfelsed sediment	Fine sandstone/siltstone with much secondary biotite	Bt
PND-1111	Pancho Negro	66920	970880	Sandstone	Greywacke sandstone with lithic clasts, angular quartz grains, in a fine matrix of clay minerals. Secondary biotite	Qtz, bt
PND-1125	Chiquintad	69590	969910	Welded dacitic tuff	Feldspar crystals and lithic lapilli set in a red-buff glassy matrix with a strong vitroclastic texture. Much secondary carbonate	Feld, carb
PND-1129	Chiquintad	69490	969950	Andesite lava	Zoned microphenocrysts of plagioclase in fine matrix rich in secondary carbonate	Plag, carb
PND-1138	Chiquintad	70130	969980	Rhyolitic rock	Very poor thin section. Recrystallized silica-rich rock	
PND-1141	Chiquintad	70270	970060	Andesite lava	Fresh rock. Microphenocrysts of plagioclase, clinopyroxene and minor orthopyroxene (pleochroic hypersthene) in a fine, feldspathic, glassy pilotaxitic matrix	Plag, cpx, opx, feld
PND-1149	Chiquintad	69620	969810	Acid tuff	Welded dacitic or rhyolitic tuff with some feldspar? crystals. Very poor thin section	Feld
PND-1152	Chiquintad	69750	969820	Welded acid tuff	Welded acid tuff with quartz crystals. Rich in lithic lapilli. Eutaxitic groundmass	Qtz
PND-1156	Chiquintad	69760	969770	Acid tuff	Contains lithic lapilli in a fine, recrystallized quartz-feldspathic groundmass with very delicate shards	Qtz, feld
PND-1159	Chiquintad	69790	969980	Andesite lava	Altered porphyritic andesite with altered plagioclase phenocrysts in a microlithic/pilotaxitic matrix	Plag
PND-1166	Chiquintad	69970	970190	Andesite lava	Altered porphyritic andesite with much carbonate	Carbt
PND-1168	Chiquintad	69930	970150	Andesite lava	Phenocrysts of plagioclase and minor mafic phenocrysts altered to chlorite, in a fine pilotaxitic groundmass with feldspar microlites	Plag, chl, feld
PND-1171	Chiquintad	70290	970070	Intermediate crystal tuff	Very poor thin sections. Altered plagioclase crystals in a vitroclastic matrix, containing delicate cuspate shards	Plag
PND-1173	Chiquintad	70480	970060	Andesite lava	Altered. Phenocrysts of plagioclase and chloritised clinopyroxene? in a fine matrix	Plag, chl, cpx
PND-1174	Chiquintad	70510	970050	Andesite lava	Altered. Phenocrysts of plagioclase altered to carbonate and of mafic mineral altered to chlorite, in a fine, altered matrix rich in microlites and fine laths of feldspar	Plag, carbt, chl, feld
PND-1178	Chiquintad	70660	969990	Andesite lava	Phenocrysts of plagioclase and a mafic mineral altered to chlorite, in a fluxioned/pilotaxitic feldspathic matrix	Plag, chl, feld
PND-1181	Chiquintad	70950	969900	Dacitic tuff	Welded dacitic tuff containing lithic lapilli, broken quartz and feldspar crystals in an intensely welded pale brown glassy matrix	Qtz, feld

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-1192	Gualleturo	72140	971230	Andesite lava	Altered andesite lava. Plagioclase and clinopyroxene phenocrysts altered to chlorite and carbonate in a pilotaxitic matrix	Plag, cpx, chl, carbt
PND-1195	Gualleturo	72130	971480	Andesite lava	Highly altered amygdaloidal lava with very abundant amygdales infilled with chlorite. Abundant calcite	Chl, calc
PND-1196	Gualleturo	72120	971520	Andesite lava	Altered andesite lava. Microphenocrysts of plagioclase in a very fine glassy/microlithic matrix	Plag
PND-1210	Juncal	72490	972410	Hornblende dacite tuff	Welded dacitic tuff with glassy matrix. Good vitroclastic, texture with shards. Broken crystals of plagioclase, quartz, hornblende and minor biotite. Lithic clasts of andesite lava	Plag, qtz, hbl, bt
PND-1220	Suscal	71890	973675	Hypersthene andesite lava	Fresh andesite lava with phenocrysts of plagioclase, magnetite and minor amounts of pleochroic hypersthene in a finely recrystallized matrix	Plag, mag, opx
PND-1231	Gualleturo	71810	972060	Andesite lava	Altered andesite lava. Plagioclase phenocrysts altered to calcite and completely chloritised mafic phenocrysts in a fine feldspathic groundmass with pilotaxitic texture	Plag, calc, chl, feld
PND-1235	Gualleturo	71950	972260	Andesite/dacitic lava	Altered andesite lava, similar to 1231. Epidotised plagioclase phenocrysts and chloritised mafic phenocrysts in a fine feldspathic groundmass with pilotaxitic texture	Epid, plag, chl, feld
PND-1249	Gualleturo	71820	970720	Andesite lava	Porphyritic andesite lava. Phenocrysts of plagioclase and chloritised mafics in a fine feldspathic matrix with a pilotaxitic fabric	Plag, chl, feld
PND-1251	Gualleturo	71810	970540	Andesite lava	Altered andesite lava. Phenocrysts of plagioclase partly altered to calcite, minor amounts of small mafic phenocrysts altered to chlorite and calcite, in a fine, altered feldspathic matrix with finely divided magnetite	Plag, calc, chl, feld, mag
PND-1259	Cuenca	71140	968270	Andesite lava	Altered andesitic lavas. Phenocrysts of plagioclase and less common mafic phenocrysts altered to chlorite in a pilotaxitic matrix of feldspar microlites with magnetite	Plag, chl, feld, mag
PND-1330	Pijilí	66340	968450	Amphibolite	Fine-grained equigranular hornblende-rich rock. Composed predominantly of hornblende and some intergranular quartz	Hbl, qtz
PND-1333	Pijilí	66390	977910	Sheared basalt	Extremely poor-quality thin section. Highly sheared and altered rock with deformed quartz veinlets. In places remnants of uralitized basalt can be recognised	Qtz
PND-1368	Chiquintad	69547	979920	Welded acid tuff	Extremely poor-quality thin section. Pale brown glassy vitroclastic matrix. Strongly welded with deformed pumices. Crystals of feldspar	Feld
PND-1372	Molleturo	69389	970030	Welded dacitic tuff	Extremely poor-quality thin section. Strongly welded acid tuff with feldspar crystals and lithic clasts	
PND-1376	Chiquintad	69495	979110	Dacitic lava	Phenocrysts of plagioclase and numerous hornblende crystals pseudomorphs by magnetite. Rare euhedral biotite microphenocrysts	Plag, hbl, mag, bt
PND-1379	Gualleturo	69617	979672	Altered rock	Extremely poor-quality thin section. Porphyritic, chlorite after amphibole	Chl, amph
PND-1380	Gualleturo	69570	970800	Hornblende diorite	Extremely poor-quality thin section.	
PND-1384	Pancho Negro	69290	970840	Altered acid tuff	Very poor thin section. Altered acid tuff. Broken quartz crystals in a very fine intensely sericitised groundmass with possible 'ghost' or relict shardic fabrics. Same rock as PND-1390?	Qtz, seric
PND-1388	Pancho Negro	69030	970930	Andesite/basaltic andesite	Very poor thin section. Fine-medium grained basaltic andesite/andesite	
PND-1390	Pancho Negro	69000	960970	Welded acid tuff	Very poor thin section. Large embayed and rounded quartz crystals in a very fine silicic, altered, glassy matrix. Relict texture with pumice lapilli plastered around quartz crystals indicating rock is welded. Very similar rock to PND-1384	Qtz
PND-1410	Chiquintad	70580	969212	Acid volcanic rock	Poor thin section. Quartz crystals in a recrystallized silicic matrix. Possibly an acid lava	Qtz
PND-1423	Chiquintad	71156	969899		Exceptionally poor-quality thin section – unusable	
PND-1425	Chiquintad	71135	969875	Dacitic lapilli tuff	Poor thin section. Altered (carbonated) intermediate-acid tuff. Broken crystals, some lithic clasts, including clasts of acid tuff, some pumice lapilli	Carbt
PND-1450	Gualleturo	70783	971912	Dacitic tuff	Altered-carbonated. Numerous broken and angular feldspar crystals and less common quartz crystals and lithic clasts in a fine carbonated matrix.	Carbt, feld, qtz
PND-1472	Gualleturo	70739	972189	Dacitic tuff	Extremely poor thin section. Numerous broken crystals in a fine matrix	
PND-1495	Suscal	71112	973542		Extremely poor thin section – unusable	
PND-1499	Pancho Negro	67272	970873	Sandstone	Fine grained quartz-feldspathic sandstone. Carbonated	Qtz, feld, carbt
PND-1500	Pancho Negro	67253	970825	Tuff?	Extremely poor thin section. Possible tuff	
PND-1504	Pancho Negro	67270	970540	Sheared basalt	Extremely poor thin section. Basalt with cataclastic texture. Numerous broken pyroxene crystals	Px

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-1603	Cuenca	71097	968251	Andesite/microdiorite	Microphenocrysts of zoned plagioclase, clinopyroxene, altered orthopyroxene and interstitial quartz	Plag, cpx, opx, qtz
PND-1604	Cuenca	71050	968250	Welded dacitic tuff	Feldspar crystals, accessory quartz crystals, small pumice lapilli and minor lithic lapilli on a welded, vitroclastic groundmass. Strongly chloritised and sericitised	Feld, qtz, chl, seric
PND-1623A	Molleturo	67200	970050	Basaltic tuff-hyaloclastite	Altered feldspars, lithic lapilli and vesicular 'scoria clasts', with chloritised glass shards. Much chlorite and epidote	Feld, chl, epid
PND-1624	Molleturo	67264	970118	Rhyolitic tuff	Rich in crystals. Numerous euhedral and broken crystals of quartz many of which are embayed. K-feldspar and chloritised-epidotised mafic crystals. Large tubular pumice lapilli and some lithic clasts	Qtz, feld, chl, epid
PND-1628	Chaucha	69110	978430	Dacitic tuff	Very rich in rounded, embayed and broken quartz crystals, feldspars and lithic clasts in a fine brown glassy matrix. Some epidote and chlorite. Deformed and welded dark green vesicular scoria/pumice fiamme (poorly vesicular clots of original magma)	Qtz, feld, epid, chl
PND-1634	Chaucha	68834	968512	Andesitic tuff	Numerous broken feldspar and quartz crystals and lithic clasts. Some shards visible in matrix	Feld, qtz
PND-1635	Chaucha	68812	968531	Hornblende andesite lava	Abundant pale green-brown hornblende crystals, complexly zoned plagioclase and magnetite in a crystalline feldspathic groundmass	Hbl, plag, mag, feld
PND-1641	Molleturo	68822	968765	Andesite	Microporphyritic. Numerous magnetite pseudomorphs after hornblende. Chlorite and epidote after plagioclase and mafic phenocrysts. Very fine matrix of feldspar laths and microlites	Hbl, chl, epid, plag, feld
PND-1645	Chiquintad	70350	970350	Altered andesite/dacite lava?	Phenocrysts of plagioclase and magnetite after pyroxene? in a recrystallized quartz-feldspathic matrix. Much secondary quartz, calcite and sericite. Possibly hornfelsed. Banded rock in outcrop	Plag, mag, px, qtz, feld, calc, seric
PND-1647	Chiquintad	70285	970250	Acid (dacitic?) tuff	Magnetite pseudomorphs after mafic phenocrysts, some altered feldspar crystals, small lithic and low-density pumice lapilli, in a fine recrystallized quartz-feldspathic, vitroclastic groundmass with abundant delicate, cuspate shards with vesicles	Mag, feld, qtz
PND-1651	Gualleturo	69910	970860	Altered andesite lava	Phenocrysts of plagioclase sericitised, and mafics completely altered to chlorite and epidote. Cognate microdioritic xenoliths in a finely recrystallized groundmass	Plag, seric, chl, epid
PND-1652	Gualleturo	69876	971002	Andesitic-dacitic lapilli tuff	Crystals of feldspar, minor quartz and magnetite pseudomorphs after amphibole. Numerous lithic lapilli of andesitic lava. Matrix altered to calcite, sericite and secondary quartz, but with clear vitroclastic texture with undeformed cuspate shards	Qtz, mag, amph, calc, seric
PND-1657	Gualleturo	69734	971324	Welded rhyolitic crystal tuff	Very rich in crystals of plagioclase, alkali feldspar, euhedral and embayed quartz crystals, minor altered biotite and magnetite, and some lithic lapilli. Strongly welded vitroclastic matrix, recrystallized but almost glassy	Plag, feld, qtz, bt, mag
PND-1658	Gualleturo	69735	971335	Welded rhyolitic tuff	Crystals of quartz and lithic clasts of acid tuff in an intensely welded vitroclastic matrix with fiamme of deformed pumice. Glassy matrix altered to calcite and sericite	Qtz, calc, seric
PND-1659	Gualleturo	69743	971369	Microporphyritic basalt	Microphenocrysts of plagioclase, euhedral cpx and magnetite in a fine matrix of skeletal plagioclase laths. Some chlorite, possibly after a mafic phase	Plag, cpx, mag, chl
PND-1665	Gualleturo	69896	971613	Andesite lava	Sample 1665A. Microphenocrysts of plagioclase. Very small pseudomorphs of magnetite and chlorite after amphibole in a matrix of flow-aligned-pilotaxitic plagioclase laths and microlites	Plag, mag, chl, amph
PND-1675	Gualleturo	70200	972180	Rhyolitic crystal lithic tuff	Crystals of quartz, feldspar and magnetite, and numerous small lithic lapilli, mainly of lava, in a very fine glassy matrix	Qtz, feld, mag
PND-1704	Suscal	72040	974011	Hornblende andesite microbreccia	Polymictic clasts of hornblende andesite lava in a fine andesitic matrix. Matrix 'dusty', crystal-rich, possibly the matrix of a block-and-ash flow	Hbl
PND-1715	Juncal	72631	974144	Pyroxene andesite microbreccia	Clasts of glassy andesite lava in a fine 'dusty' andesitic matrix containing much dust and broken crystals. Clasts of andesite contain phenocrysts of plagioclase, cpx and magnetite	Plag, cpx, mag
PND-1731	Juncal	72436	973955	Andesitic volcanic sandstone	Numerous angular grains of plagioclase, hornblende, cpx and minor quartz supported in a fine 'dirty' matrix. Wacke texture	Plag, hbl, cpx, qtz
PND-1732	Suscal	71669	972738	Hornblende andesite clast	Clast from boulder conglomerate. Numerous fresh, strongly zoned plagioclase phenocrysts and partly oxidised-fresh brown hornblende set in a fine feldspathic groundmass	Plag, hbl, feld
PND-1733	Alausí	72900	976320	Volcanic sandstone	Poorly sorted, composed of numerous angular to subangular grains of feldspar, quartz and lithic clasts, minor opx? and magnetite, supported in a chloritic groundmass with some calcite	Feld, qtz, opx, mag, chl, calc
PND-1734	Matilde Esther	72156	976918	Acid crystal tuff	Numerous crystals of alkali feldspar, some quartz and lithic clasts. Interstices consists of deformed vesicular fiamme which are altered to chlorite and calcite	Feld, qtz, chl, calc
PND-1738	Chiquintad	69950	969900	Altered andesite dyke or lava?	Phenocrysts of plagioclase, rare hornblende altered to magnetite, and chloritised mafics in a very fine matrix with much quartz and calcite	Plag, hbl, mag, chl, qtz, calc
PND-1740	Chiquintad	69880	969710	Dacitic crystal tuff	Altered. Possibly poorly-sorted volcanic sediment. Numerous crystals of alkali feldspar and plagioclase, a few large euhedral-subhedral embayed crystals of quartz, some lithic clasts. Chlorite and calcite	Feld, plag, qtz, chl, calc
PND-1755	Gualleturo	70220	971750	Andesite lava	Euhedral phenocrysts of plagioclase, cpx, magnetite and numerous chlorite pseudomorphs after a mafic mineral, in a very fine recrystallized glassy matrix	Plag, cpx, mag, chl
PND-1769	Alausí	72420	975280	Andesitic tuff?	Numerous feldspar crystals, epidote, no mafics in a recrystallized matrix	Epid, epid

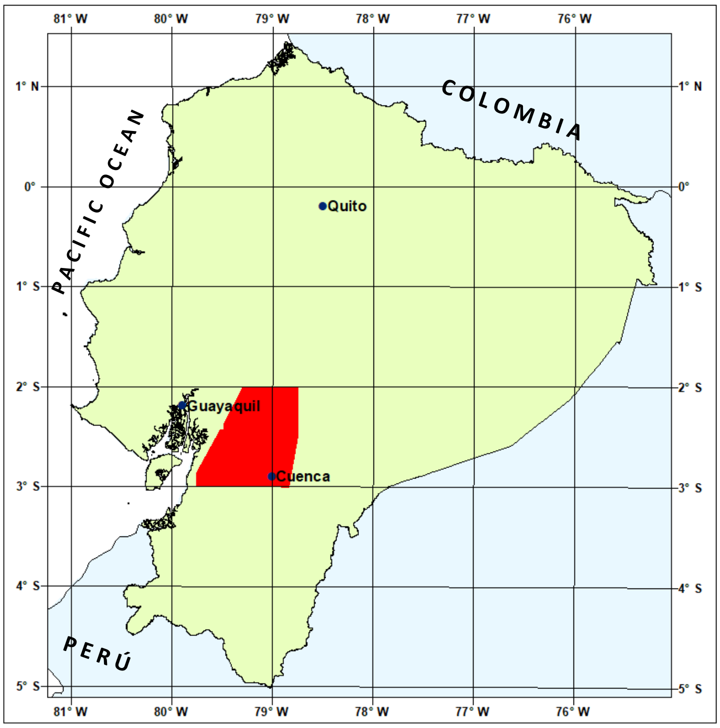
Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-1774	Alausí	72680	975160	Volcanic sandstone	Poorly sorted angular grains of feldspar, quartz, magnetite and lithic clasts	Feld, qtz, mag
PND-1785	La Troncal	69250	973040	Basaltic tuff-hyaloclastite	Numerous plagioclase crystals with glassy fiamme or deformed shards of scoria. Much chloritised glass and epidote veinlets of epidote and calcite	Plag, chl, epid, calc
PND-1805	Chaucha	68580	968410	Andesitic crystal tuff	Broken crystals of plagioclase and chlorite, epidote and oxide, in a fine dusty matrix rich in broken crystal fragments and recrystallized glassy fiamme	Plag, chl, epid
PND-1807	Chaucha	68529	968385	Altered andesitic crystal tuff	Numerous feldspar crystals-sericitised, chloritised and epidotised, in a welded matrix with deformed fiamme	Feld, chl, epid
PND-1809	Chaucha	68470	968300	Altered andesitic lava?	Feldspar phenocrysts altered to epidote and mafics altered to chlorite and epidote in a very pilotaxitic matrix with chlorite	Feld, epid, chl
PND-1815	Chaucha	69360	968480	Altered andesite lava	Altered plagioclase phenocrysts, minor rounded quartz phenocrysts. Much secondary carbonate	Plag, qtz, carbt
PND-1816	Chaucha	69355	968470	Andesite clast	Clast in breccia. Strongly altered andesite lava. Much calcite and chlorite	Calc, chl
PND-1820	Chaucha	68180	966855	Welded rhyolitic crystal tuff	Abundant broken and embayed quartz crystals, plagioclase, chloritised biotite in a pale brown glassy chloritised vitroclastic groundmass. Spherulitic chlorite. Numerous clasts of red-brown, oxidised porphyritic andesite lava	Qtz, plag, chl, bt
PND-1828	Chaucha	67885	967165	Welded dacitic tuff	Minor broken feldspar and quartz crystals. Mafic crystals altered to epidote. Very fine sericitised matrix with welded sericitised fiamme	Feld, qtz, epid, seric
PND-1833	Chaucha	68630	968625	Andesite lava clast	Clast from breccia. Altered andesite lava. Feldspar phenocrysts replaced by calcite in a fine pilotaxitic groundmass with calcite, chlorite and magnetite	Feld, calc, chl, mag
PND-1834	Chaucha	68565	968650	Altered andesite lava	Microphenocrysts of plagioclase altered to calcite and epidote, and mafics completely altered to chlorite and magnetite. In a very fine pilotaxitic groundmass	Plag, calc, epid, chl, mag
PND-1835	Chaucha	68550	968645	Intermediate crystal lithic tuff	Andesitic/dacitic tuff with abundant feldspar crystals some quartz and abundant lithic clasts – mostly of andesitic/dacitic lava. Much epidote and chlorite. Groundmass fine, glassy and welded?	Feld, qtz, epid, chl
PND-1840	Molleturo	69215	969940	Dacitic lava	Microporphyritic. Plagioclase phenocrysts and less common rounded and embayed quartz phenocrysts. Altered mafic phenocrysts. Feldspathic groundmass	Plag, qtz
PND-1843	Molleturo	69175	969980	Welded rhyolitic tuff	Altered. Intensely welded vitroclastic texture. Strongly altered to sericite and calcite	Seric, calc
PND-1848	Molleturo	69095	969950	Altered andesitic tuff	Strongly altered. Much calcite, chlorite and sericite. Lithic clasts of andesite	Calc, chl, seric
PND-1850	Molleturo	69080	969950	Andesite lava	Fresh plagioclase, some chloritised cpx in matrix of feldspar laths. Similar to sample PND-1840	Plag, chl, cpx, feld
PND-1851	Chiquintad	70495	970045	Altered andesite lava	Altered microporphyritic andesite lava. Epidotised feldspar, chloritised mafics, some magnetite in a feldspathic matrix	Feld, chl, mag
PND-1858	Chiquintad	70620	970440	Altered andesite lava	Strongly altered porphyritic andesite lava. Pilotaxitic groundmass with much calcite and carbonate	Calc, carbt
PND-1872	Chiquintad	70420	969525	Altered andesite lava	Chloritised and actinolitised cpx. Matrix of feldspar laths	Chl, actl, cpx, feld
PND-1874	Chiquintad	69365	969295	Welded andesitic tuff	Strongly welded crystal lithic tuff. Lithic lapilli of andesite lava	
PND-1898	Chiquintad	69590	968935	Altered andesite lava	Phenocrysts of plagioclase and mafics altered to chlorite and calcite	Plag, chl, calc
PND-1900	Chiquintad	69555	968910	Andesitic lithic lapilli tuff	Abundant clasts of andesitic lava and chloritised fiamme/scoria. Looks like a scoria flow	Chl
PND-1903	Molleturo	69275	969410	Dacitic lava	Phenocrysts of feldspar in a very fine recrystallized groundmass	Feld
PND-1905	Molleturo	69225	969465	Welded dacitic tuff	Abundant rounded and embayed quartz crystals, feldspars and lithic clasts in a welded vitroclastic matrix of deformed shards and fiamme	Qtz, feld
PND-1908	Molleturo	69170	969480	Andesitic breccia matrix	Matrix to breccia. Andesite lava matrix of pilotaxitic laths and microlites of feldspar with phenocrysts of feldspar and chloritised mafics	Feld, chl
PND-1910	Molleturo	69150	969500	Welded dacitic/rhyolitic tuff	Abundant rounded and embayed quartz crystals, feldspar altered to calcite and sericite, biotite altered to chlorite. Numerous andesite lava clasts. Welded glassy-vitroclastic groundmass	Qtz, feld, calc, seric, bt, chl
PND-1915	Chiquintad	70470	968905	Welded andesitic/dacitic tuff	Altered-carbonated. Clasts of andesite lava in scoriaceous welded/agglutinated, brown glassy vitroclastic groundmass. Clasts are feldsparphyric. Minor quartz crystals	Carbt, feld, qtz
PND-1919	Chiquintad	70435	968855	Andesitic tuff	Andesitic tuff/scoria flow deposit. Fragments of andesitic lava in an agglutinated/welded matrix of brown andesitic glassy scoria/fiamme	
PND-1923	Chiquintad	70360	968670	Andesitic tuff/breccia	Clasts of fine grained pilotaxitic andesite lava in a matrix of the same material. Much carbonate, chlorite and sericite	Carbt, chl, seric
PND-1927	Chiquintad	70600	969000	Andesitic lapilli tuff	Similar to samples 1915/1923. Altered-much carbonate and sericite. Lithic clasts of andesite lava, feldspars and some quartz crystals in fine pale brown welded vitroclastic matrix with shards	Carbt, seric, feld, qtz
PND-1929	Chiquintad	70670	969055	Andesite lava	Snow-flake recrystallization of fine matrix. Sericitised feldspar phenocrysts, chlorite and carbonate	Feld, chl, carbt

Sample	Sheet	UTMX	UTMY	Rock type	Description	Minerals
PND-1931	Chiquintad	70715	969110	Andesitic lithic tuff	Plagioclase crystals and lapilli of andesite lava, in a fine glassy matrix including deformed scoria. Much calcite, chlorite and epidote. Mafic crystals altered to calcite	Plag, calc, chl, epid
PND-1938	Molleturo	69370	968925	Andesitic lithic tuff	Numerous lithic lapilli of fine pilotaxitic andesite lava, plagioclase crystals and sporadic quartz crystals. Dusty matrix with possible shards	Plag, qtz
PND-1941	Molleturo	69345	968880	Rhyolitic tuff	Fine-grained rhyolitic tuff. Sporadic crystals of plagioclase, minor quartz and rare lithic clasts of pilotaxitic lava and tuff. Very fine dusty matrix with some visible shards	Plag, qtz
PND-1942	Molleturo	69335	968845	Welded dacitic tuff	Intensely welded dacitic tuff. Abundant feldspar crystals and broken, rounded and embayed quartz crystals, some biotite, magnetite and chlorite after mafics. Some lithic clasts. Brown glassy matrix with intense welding/eutaxitic fabric	Feld, qtz, bt, mag, chl
PND-1958	Chiquintad	68345	969015	Welded rhyolitic tuff	Crystals of feldspar, quartz and magnetite in very fine recrystallized groundmass with good vitroclastic texture with shards. Sericitic alteration	Feld, qtz, mag, seric
PND-1961	Chiquintad	70500	970085	Altered andesite lava	Chlorite, calcite, epidote and sericite	Chl, calc, epid, seric
PND-1962	Molleturo	68370	968940	Welded dacitic tuff	Numerous rounded and embayed quartz crystals, feldspars and chlorite. Strongly welded pale brown glassy vitroclastic matrix with tubular pumice	Qtz, feld, chl
PND-1967	Molleturo	68405	968825	Dacitic lava	Partly altered. Minor cpx altered to chlorite, much magnetite some after amphibole, in a recrystallized quart-feldspathic matrix	Cpx, chl, mag, amph, qtz, feld
PND-1969	Molleturo	68445	968800	Dacitic tuff	Numerous crystals of quartz, feldspar and much biotite in a fine groundmass. Altered. Possible plutonic xenoliths	Qtz, feld, bt
PND-1975	Molleturo	68330	968720	Andesitic tuff	Lithic crystal andesitic tuff. Altered – chlorite, epidote, actinolite	Chl, epid, actl
PND-1977	Molleturo	68375	968690	Andesitic-dacitic tuff	Crystals of feldspar and some clasts of lava in very fine dusty/recrystallized matrix. Possible chloritised fiamme. Much chlorite, epidote and carbonate	Feld, chl, epid, carbt
PND-1979	Molleturo	68390	968660	Altered rock	Strongly altered andesite lava? Phenocrysts of plagioclase. Much chlorite, epidote and magnetite	Plag, chl, epid, mag
PND-1980	Molleturo	68400	968650	Andesitic-dacitic tuff?	Very fine grained and strongly altered to sericite and chlorite	Seric, chl
PND-1985	Chiquintad	70250	968730	Dacitic tuff	Feldspar crystals, minor quartz and lithic clasts in finely recrystallized groundmass. Lithic clast of andesite lava. Much sericite and chlorite	Feld, qtz, seric, chl
PND-2004	Matilde Esther	70090	977380	Basic volcanic sandstone	Angular grains of feldspar and abundant chloritised/sideromelane glass fragments/shards, magnetite and lithic grains of fine variolitic basalt. Much chloritised glass	Chl, mag
PND-2005	Matilde Esther	69980	977000	Basaltic tuff/hyaloclastite	Highly expanded vesicular basaltic glass (scoria) lapilli, and shards. Chloritised. Some epidote	Chl, epid
PND-2010	Matilde Esther	71080	976990	Basaltic tuff-sandstone	Reworked basaltic tuff or volcanic sandstone. Feldspar crystals and numerous cuspate-shaped vesicular grains of basalt and basaltic glass shards and vesicular scoria lapilli. Chloritised glass	Feld, chl
PND-2013	Matilde Esther	70960	976740	Hyaloclastite	Glass shards and ragged lapilli of highly vesicular basaltic glass	
PND-2017	Matilde Esther	71510	977170	Basalt tuff	Subaqueous basaltic tuff-reworked hyaloclastite. Chloritised shards of glass and very fine-grained basalt lava fragments. Quench textures	
PND-2020	Matilde Esther	71480	976310	Altered andesite lava	Plagioclase phenocrysts and chlorite pseudomorphs in a fine matrix of plagioclase laths	Plag, chl
PND-2021	Matilde Esther	71310	976180	Altered hornblende andesite lava	Phenocrysts of plagioclase, hornblende and minor quartz in a very fine dusty and recrystallized matrix. Much chlorite, epidote and carbonate. Possible chloritised fiamme	Plag, hbl, qtz, chl, epid, carbt

APPENDIX 4 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 2°00’ AND 3°00’ S

RADIOMETRIC DATES



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 2 AREA)

QUITO, 1997

Radiometric dates

The table below presents details of new radiometric dates obtained during the course of the project. The fission-track dates were obtained from zircons and were determined at the Geological Institute, ETH Zurich by Michael Steinmann. The K/Ar dates were determined on hornblende crystals at the Scottish University's Reactor Centre, East Kilbride.

Table 1. New radiometric dates

Sample No.	UTMX	UTMY	Lithological unit	Rock type	Method	Age (Ma)
M3-946	7309	97776	Cisarán Fm.	Andesitic lava	Fission track	6.9 ± 0.7
PND-272	6999	96918	Tomebamba Unit	Andesitic ash-flow tuff	Fission track	34.1 ± 1.3
PND-1083	7429	97441	Cisarán Fm.	Andesitic lava	K/Ar	7.15 ± 0.38
PND-1438	6887	97012	Plancharumi Fm.	Rhyolitic air-fall tuff	Fission track	25.7 ± 1.1
PND-1621	6907	96793	Soldados Fm.	Dacitic ash-flow tuff	Fission track	29.8 ± 1.2
PND-1692	6998	97252	Ocaña Fm.	Dacitic ash-flow tuff	Fission track	37.0 ± 1.5
PND-1693	7217	97192	Cerro Caucay Fm.	Rhyolitic ash-flow tuff	Fission track	30.2 ± 1.1
PND-1694	7228	97208	Cerro Caucay Fm.	Rhyolitic ash-flow tuff	Fission track	27.0 ± 1.0
PND-1698	7164	97692	Ocaña Fm.	Dacitic ash-flow tuff	Fission track	38.6 ± 1.3
PND-1699	7189	97429		Diorite intrusion	K/Ar	7.59 ± 0.35
PND-1734	7215	97692	Angamarca Group	Dacitic ash-flow tuff	Fission track	37.8 ± 3.5